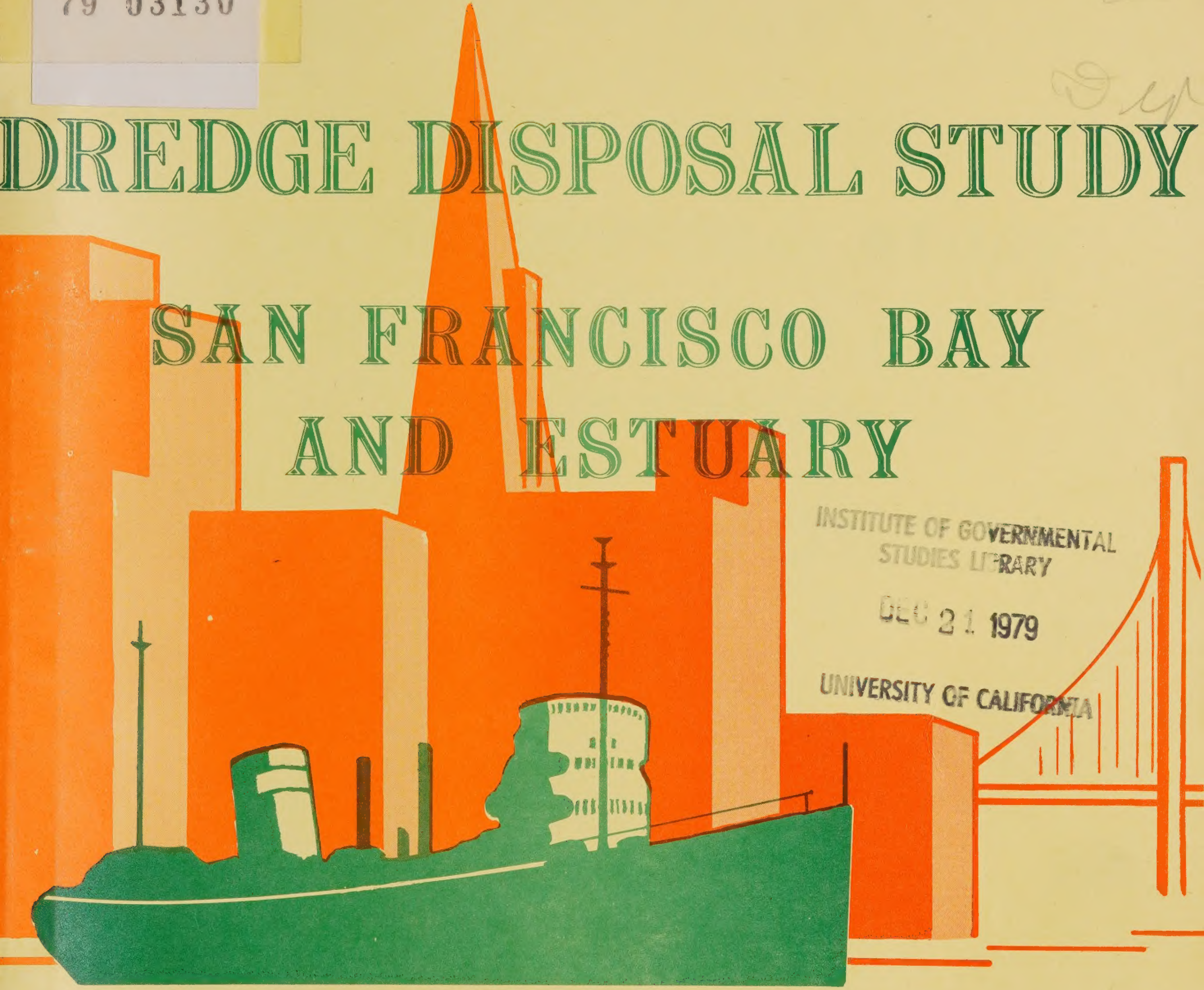
DREDGE DISPOSAL STUDY

SAN FRANCISCO BAY AND ESTUARY



[San Francisco bay marine research center
San Francisco bay
Dredging--California--S.F. bay
Marshes-- " -- " " region

U.S. ARMY CORPS OF ENGINEERS
SAN FRANCISCO DISTRICT

MAIN REPORT

FEBRUARY 1977

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U.S. Army Engineer District, San Francisco

Corps of Engineers

211 Main Street

San Francisco, CA 94105

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INTRODUCTION

PURPOSE AND INITIATION

In recent years a major conflict developed between environmental and development interests relative to the effects of dredged sediment disposal in San Francisco Bay and estuary. The controversy was due to the lack of sufficient basic information on the effects of disposal to establish guidelines for protecting the environment and yet maintain the viability of commercial and national defense navigation.

The Corps of Engineers has responsibility for dredging operations in San Francisco Bay area in terms of maintenance of Federal projects and administration of the permit program under Section 404(b) of the Federal Water Pollution Control Act Amendments of 1972 and the Marine Protection, Research and Sanctuaries Act of 1972, and is vitally interested in developing accurate information to guide the decision making. Therefore, the San Francisco District undertook a comprehensive, in-depth study to identify the environmental impacts of dredging with open water disposal and to examine alternative disposal methods to eliminate or mitigate identified problems.

An investigation was initiated in December 1970 with background sampling on the San Francisco Bar. Further investigations were made in June 1971 when the hopper dredge "BIDDLE" began deepening the Main Ship Channel across the San Francisco Bar. In addition to continued biological and sediment sampling and water quality monitoring, diving operations were expanded on the Bar in February 1972 to continue the evaluation of the disposal operations.

Prior to the Bar studies, during the period September 1967 to August 1969, the San Francisco District had sponsored field and laboratory studies by the U.S. Fish and Wildlife Service to determine effects dredging and sediment disposal would have on fish and wildlife environment in selected and representative reaches of San Francisco and San Pablo Bay. Subsequent informal discussions with other agencies and individuals resulted in a list of questions requiring investigation to determine the environmental impacts of dredging and disposal operations. During the summer of 1971, the San Francisco District organized the list into a formal study proposal and distributed a draft of the Preliminary Plan of Study to staff level representatives of Federal, State and Regional agencies having regulatory functions for dredging in the San Francisco Bay Area for review and comment. This resulting study was authorized by the Office of Chief of Engineers on dated 22 March 1972, under the authorized project San Francisco Harbor, California.

SCOPE OF STUDY

The basic concept of the overall study was to address to the greatest extent possible the mechanisms involved and the interrelationships of the various physical, chemical and biological parameters being influenced by the dredging activity or influencing the dredging activities. The concept of baseline type study was not considered to be fully adequate because of the size and complexity of the Bay and the lack of ability to determine cause-effect relationships from baseline changes. Baseline studies were, however, conducted to the extent necessary and other individual elements were conducted in such a way that resulting data would serve as input to baseline descriptions.

The study was set up to be problem specific and site specific to San Francisco Bay, recognizing that it may have value to other areas. Thirteen study elements were identified (excluding the studies on the San Francisco Bar). Each of the thirteen elements addressed aspects of dredging within the Bay using either open water disposal or alternative disposal methods.

The first study category, dealing with dredging with open water disposal in the Bay, involves ten of thirteen study elements, and is further divided into three levels of studies; the characterization of the physical, chemical and biological factors; first level interaction studies; and multiple interaction studies. These ten study elements are:

<u>Descriptive</u>

POLLUTANT DISTRIBUTION WATER COLUMN	Characterize physical factors
OXYGEN SAG MATERIAL RELEASE	
BIOLOGICAL COMMUNITY	- Characterize Biota (Benthic)
CRYSTALLINE MATRIX	- Characterize Sediment Chemistry

<u>First Level Interactions</u>

PHYSICAL IMPACT	- Relate Physical and Biological
POLLUTANT UPTAKE	- Relate Chemical and Biological
DREDGING TECHNOLOGY	- Relate Physical and Equipment

<u>Multiple Interaction</u>

POLLUTANT AVAILABILITY	- Integration of Factors

The second study category, dealing with alternative disposal methods, presents information specific to San Francisco Bay on the procedure for each alternative and a preliminary evaluation of impact and relative costs associated with all disposal methods. There are three study elements in this category:

LAND DISPOSAL
MARSH DEVELOPMENT
OCEAN DISPOSAL

The thirteen study elements were accomplished through a combination of in-house efforts, contracts with engineering firms and research institutes, and interagency agreements. Table 1 is a work summary of the study elements.

COORDINATION

The initial development of the plan of study was the outcome of informal discussions and staff level meetings over a two-year period with Federal, State and local agencies and individuals in the Bay area. In October 1971, the Dredge Advisory Group was formed with staff level representatives from Federal, State and Regional agencies having regulatory functions for dredging in San Francisco Bay. It met monthly in an informal forum to discuss both general and project-specific problems of dredging operations. In addition to reviewing the draft Plan of Study, the group received monthly briefings which included review of scopes of services and study findings. The agencies represented are:

U.S. Environmental Protection Agency
U.S. Fish and Wildlife Service
U.S. National Marine Fisheries Service
U.S. Army Corps of Engineers
California Department of Fish and Game
California State Lands Commission
California Regional Water Quality Control Board, San Francisco Region
San Francisco Bay Conservation and Development Commission
California Marine Affairs and Navigation Conference
West Coast Dredging Association

In addition to the Dredge Advisory Group, a group of consultants met several times to provide technical guidance and review during the course of the studies with major emphasis on the chemical and biological studies. The consultants were:

TABLE 1 *WORK SUMMARY*

STUDY ELEMENT	ORGANIZATION & CONTRACT	COST	WORK	PRINCIPAL INVESTIGATORS	DISTRICT COORDINATOR	REPORTING APPENDIX
SAN FRANCISCO BAR	San Francisco District	-	Conduct physical, chemical and biological monitoring and prepare appendix	John Sustar	John Sustar	A
	Towill, Inc (DACW07-71-C-0063)	$26,638	Conduct physical monitoring and current studies	William Robinson		
POLLUTANT DISTRIBUTION	San Francisco District	-	Evaluate data and prepare appendix	Richard Ecker John Hendricks	Richard Ecker	B
	Alpine Geophysical (DACW07-73-C-0039)	54,930	Conduct seismic profiling	George Tirey		
	Bartee (DACW07-73-B-0027)	44,460	Obtain core samples			
	South Pacific Division Lab (E86-73-3038)	41,714	Analyze core samples			
WATER COLUMN	San Francisco District	-	Monitor standard water quality parameters and prepare appendix	Thomas Wakeman	Thomas Wakeman	C
OXYGEN SAG	San Francisco District	-	Monitor dissolved oxygen and prepare appendix	Thomas Wakeman	John Sustar	C
	Brown and Caldwell (DACW07-73-C-0051)	14,150	Monitor dissolved oxygen	Craig Walton		
	Environmental Quality Anal. (DACW07-74-C-0044)	6,250	Monitor dissolved oxygen	Robert D. Smith		
BIOLOGICAL COMMUNITY	Stanford Research Institute (DACW07-73-C-0059) (DACW07-74-C-0005)	41,200 164,162	Collect samples for identification of infauna benthic organisms, characterize chemistry of sediment and water and prepare appendix	Dr. David Liu	Thomas Wakeman	D
MATERIAL RELEASE	San Francisco District	-	Conduct sampling program, evaluate data and prepare appendix	Richard Ecker Cpt William Harvey	Richard Ecker	E
	Waterways Experiment Station (E86-73-3026) with subcont. Stanford Research Institute	495,500	Develop tracer technique, introduce tracer and and analyze samples	Ed Leahy Burt Lane		
	Hydrologic Engineering Center (E86-75-3031)	4,656	Develop data processing program			
	Stanford Research Institute (DACW07-73-C-0075)	58,195	Develop numerical sediment transport model	Lynn Spraggs		
CRYSTALLINE MATRIX	Battelle Northwest (DACW07-73-C-0080)	142,775	Perform chemical analysis of sediments including fractionation and desorption and prepare appendix	Jeff Serne	Thomas Wakeman	F
PHYSICAL IMPACT	Bodega Marine Laboratory NOAA contract supplement interagency agreement	99,000	Conduct laboratory studies on affects of suspended solids temperature and dissolved oxygen on organisms and prepare appendix	Dr. Richard Peddicord	Thomas Wakeman	G
POLLUTANT UPTAKE	Lawrence Berkeley Laboratory (DACW07-73-E-4594)	99,470	Conduct field studies during dredging on mode of heavy metal uptake and prepare appendix	Victor Anderlini John Chapman	Thomas Wakeman	H
POLLUTANT AVAILABILITY	Lawrence Berkeley Laboratory ERDA interagency agreement	196,600	Conduct field studies on biological availability of heavy metals and pesticides during disposal operations and prepare appendix	Victor Anderlini John Chapman	Thomas Wakeman	I
LAND DISPOSAL	International Engineers (DACW07-73-C-0079)	141,510	Develop systems model to evaluate cost of alternative disposal methods, evaluate feasibility of using land disposal sites and prepare appendix	Ray Samuelson	Paul Knutson	J
MARSH DEVELOPMENT	San Francisco District	-	Evaluate data and prepare appendix	P... Knutson	Paul Knutson	K
	San Francisco Bay Marine Research Center (DACW07-74-C-0008)	125,690	Conduct laboratory, nursery and pilot field planting program and evaluate planting methods	Dr. Curtis Newcombe Dr. Herbert Mason Dr Kenneth Floyd		
OCEAN DISPOSAL	San Francisco District	-	Monitor water column and prepare appendix	Paul Knutson	Paul Knutson	L
	Naval Undersea Research Center interagency agreement	50,000	Conduct characterization studies and monitor sediment releases at 100-fathom site	Dr. Sachio Yamamoto		
DREDGING TECHNOLOGY	JBF Scientific Corp. (DACW07-75-C-0045)	137,900	Conduct field and laboratory simulation studies on sediment-equipment relationships in developing release patterns and prepare appendix	Edward Johanson	John Sustar	M
MAIN REPORT	San Francisco District	-	Integrate above studies	John Sustar Thomas Wakeman	John Sustar	

Dr. L. Eugene Cronin - Chesapeake Biological Laboratory, University of Maryland

Dr. John Harrison - U.S. Army Engineer Waterways Experiment Station

Dr. Sewell H. Hopkins - Texas A & M University, retired

Mr. John Ladd - California Department of Fish & Game

Dr. G. Fred Lee - University of Texas, Dallas (did not participate during last year)

Dr. William H. Patrick, Jr. - Louisiana State University

Dr. Donald J. Reish - California State University, Long Beach

The Corps of Engineers Committee on Tidal Hydraulics provided technical guidance to studies on sediment movement. Countless other individuals provided informal guidance to all of the study elements.

The study complements the Dredged Material Research Program at the Waterways Experiment Station, Vicksburg, Mississippi. Close coordination with the Station was maintained through frequent staff meetings.

DESCRIPTION OF SAN FRANCISCO BAY

PHYSIOGRAPHY

San Francisco Bay, shown in Figure 1, is a drowned valley through which passes the drainage of the great Central Basin of California. The outlet to the ocean is the Golden Gate, a 1.6 kilometer wide, 4.8 kilometer long strait with depths in excess of 90 meters. The Bay system is composed of several distinct areas separated by narrow straits. Suisun Bay at the upper end is moderately narrow and allows runoff from the Central Valley to pass quickly into the more saline areas west of the 11 kilometer long Carquinez Strait. San Pablo Bay provides the first area of extensive mixing of freshwater runoff with saline ocean water. The isolated South San Francisco Bay receives very little runoff because there are no large tributaries and several small local drainage areas are impounded.

The Bay System has an area of 1,026 square kilometers at mean lower low water and 1,191 square kilometers at mean higher high water. Extensive intertidal mudflats, encompassing an area of 166 square kilometers, are exposed at lower low water. There remains 329 square kilometers of marshland along the perimeter of the Bay's 442 kilometers shoreline. The Bay is generally shallow with two-thirds of the area less than 5.5 meters deep and only 20 percent greater than 9 meters deep.

The recent geologic landscape evolution which created San Francisco Bay has been complicated and is not clearly understood. Some general facts are known. The valley that became the Bay was a structural deformation trough formed by tectonic downwarping and faulting during the Pliocene Epoch. Subsequent structure deformations caused by crustal compression took place in the Pleistocene. The basic outline of the bay-valley as it appears today was shaped by this point in time. This valley form has been continually modified by local processes of erosion and deposition.

The river system, which became the Sacramento-San Joaquin, developed an outlet in the vicinity of the Golden Gate prior to the Pleistocene. This river system which drains the great Central Basin of California was well established in this epoch. During the Pleistocene the north-south trending hills surrounding the bay-valley were uplifted at a rate slow enough to allow the river to maintain its course to the sea and to carve deep canyons at Carquinez and at the Golden Gate.

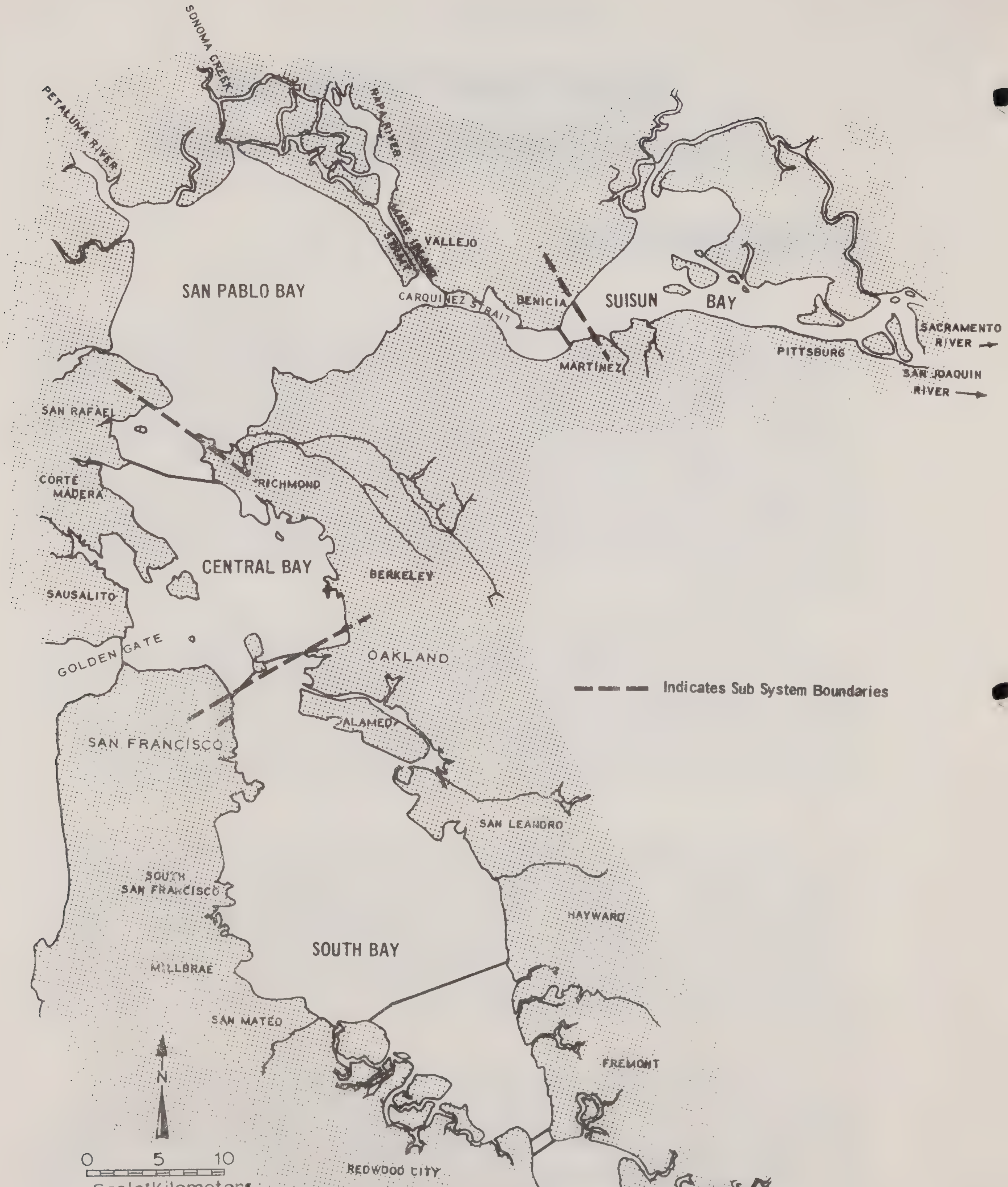


FIGURE 1 SAN FRANCISCO BAY SYSTEM

San Francisco Bay was formed by flooding of the valley during the interglacial stages of the Pleistocene and Holocene (Recent). The most recent marine transgression occurred 15,000 to 25,000 years ago with the advent of the Wisconsin interglacial stage. These fluctuating invasions of the sea into the bay-valley were, mainly, a result of eustatic rise in sea level caused by melting of massive continental glaciers and by local subsidence. The rise in sea level is estimated to have been about 90 meters. Local subsidence has also been a factor in the change of sea level in the Bay. Archaeological evidence derived from shell mound excavations on the east shore of the Bay indicated sea level has risen 7.6-9.1 meters in the last 3,500 years.

The surface area of San Francisco Bay (including marshlands) prior to 1850 is estimated to have been 2,038 square kilometers. The pre-1850 Bay consisted mostly of a shallow, shelving Bay floor with extensive sub-tidal and inter-tidal flats coupled with expanses of salt marshland, situated mainly in South Bay, San Pablo Bay and Suisun Bay.

The physical geography of the Bay has been significantly modified by land reclamation work since the middle of the nineteenth century. The purpose of historical land reclamation has differed throughout the Bay and has resulted in a variety of land use patterns on new land recovered from the Bay. Since the mid-nineteenth century, approximately 619 square kilometers or 31 percent of the Bay system has been either filled or diked-off and drained to provide new land for a range of activities.

Initial land reclamation along the shore of the Bay system was aimed at developing port facilities and maritime commerce adjacent to deep water in Central San Francisco Bay. Other early land reclamation operations were carried out to recover additional agricultural lands from salt marshlands situated mainly in South Bay, San Pablo Bay and Suisun Bay. Subsequent reclamation projects have recovered new land for salt ponds, as well as for industrial, transportation, residential and recreation uses.

The Corps of Engineers estimated the use of the 619 square kilometers of new lands as shown in Table 2.

TABLE 2

PRESENT USE OF NEW LANDS

USE	% RECLAIMED LAND
Transportation	7.2
Industrial	4.8
Residential & Commercial	3.9
Military & Reserved Lands	6.3
Recreational	26.9
Salt Ponds	24.8
Agricultural	23.2
Dumps & Vacant Lands	2.9

Of the reclaimed lands, about 40 percent are situated in Central and South San Francisco Bay, 30 percent in San Pablo Bay, and 30 percent in Suisun Bay. The largest portion of this new land (93%) was recovered from marshlands while the remaining 7 percent was recovered from inter-tidal and sub-tidal lands.

Reclamation has irrevocably changed the geometry of the Bay by reducing both the volume and surface area of Bay waters. The tidal prism has been diminished, causing a general reduction of tidal current velocities and, to a lesser extent, reduction of tidal elevations and ranges, combined with alteration of salinity in different parts of the estuary. This reduction of the tidal prism has diminished the capability of tidal currents to disperse and flush contaminants out of the Bay system. Land reclamation has reduced the surface area of the Bay by eliminating fringing tidal flats and marshlands. This has diminished the system's ability to reoxygenate Bay waters. Lowering the dissolved oxygen content of the Bay has reduced the capability of the estuary to decompose biodegradable contaminants. Tidal flats and marshes produce nutrients which serve as a base for the food web, capture ions and dissipate energy. Alteration of the submarine configuration of the Bay basin coupled with the reduced tidal prism has increased shoaling rates and changed sedimentation patterns in many areas. The accelerated shoaling rate is caused by reduced tidal current velocities, increased salinity (and therefore, flocculation), and decreased Bay volume. Surface areas and volumes have been reduced mainly around the shallow perimeter of the Bay.

CLIMATE

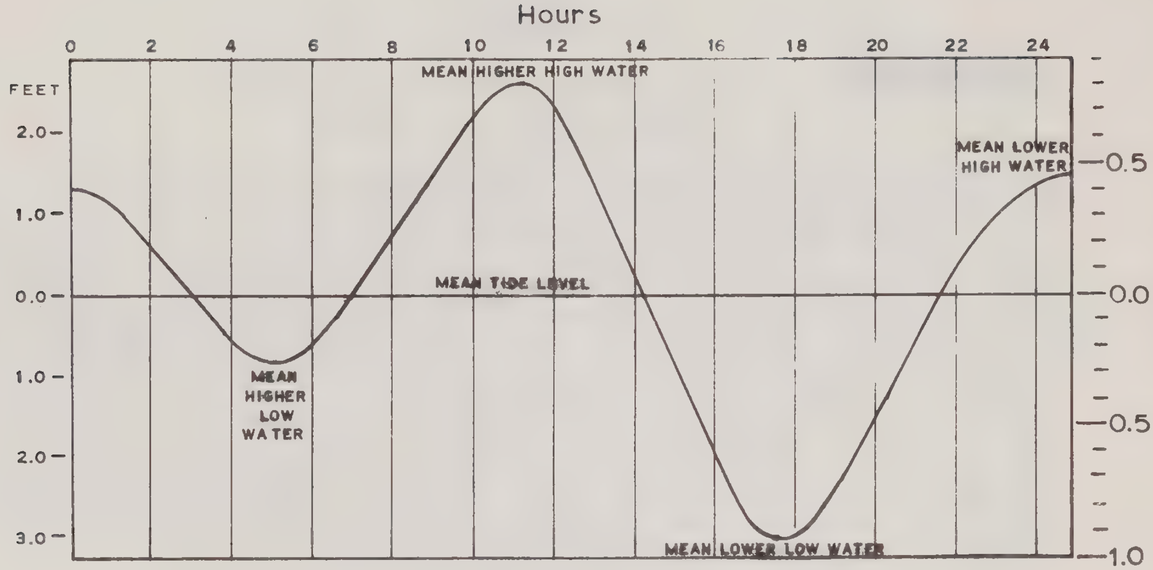
There are wide contrasts in climate within short distances around San Francisco Bay. In the summertime, temperature of the Pacific Ocean is unusually low near the coast and atmospheric pressure relatively high, while the interior of California is characterized by the opposite in both elements. This tends to intensify the landward movement of air and to make the prevailing westerly winds brisk and persistent, especially from May to August. As a result of the steady sweep of air from the Pacific, there are few extremes of heat or cold. A pronounced wet and dry season is another characteristic of the climate. On the average, almost 85 percent of the total annual rainfall occurs between November and April. Average annual rainfall varies from about 0.4 to 0.5 meters at different locations around the Bay.

TIDES

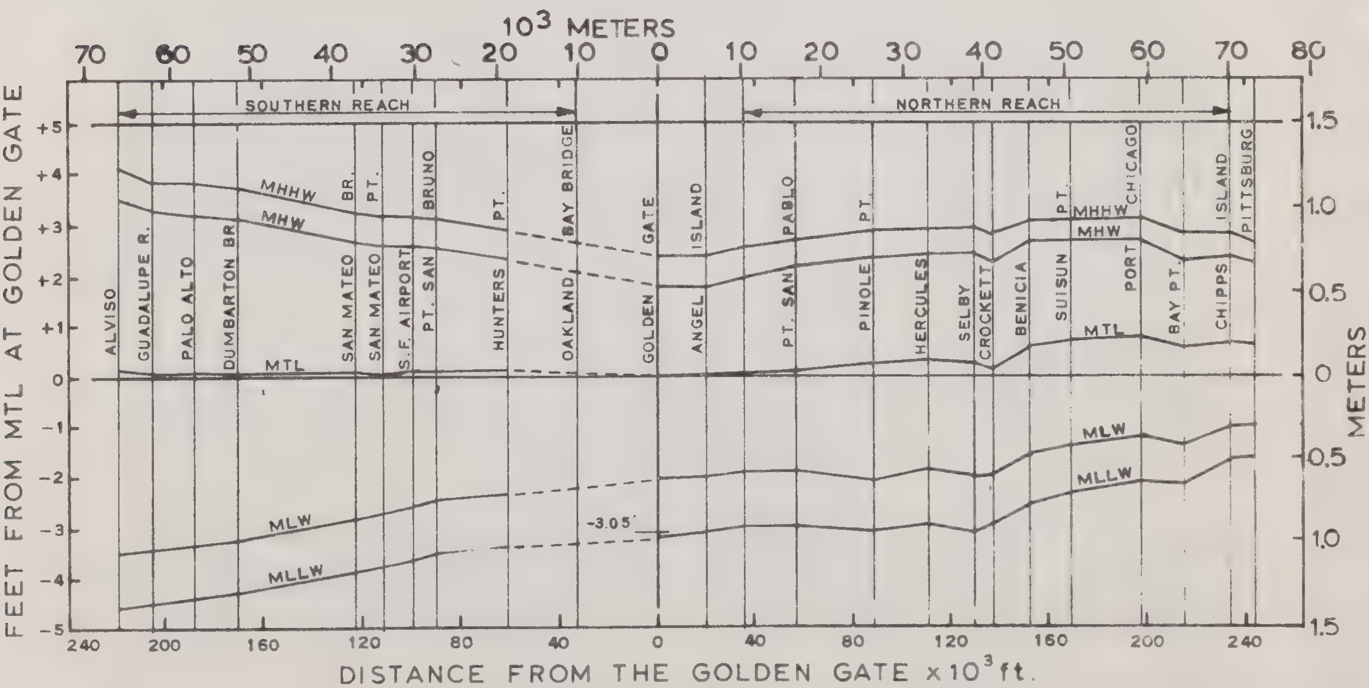
Current patterns and water surface elevations in the Bay system are determined by the effects of the configuration of the system on freshwater and tidal inflows. The submarine configuration formed by the series of broad shallow bays connected by narrow straits delays the progress of tide through the system because each successive bay must fill and empty the large volume of its tidal prism through its narrow opening. Tidal changes at Martinez on the south shore of Carquinez Strait, for example, lag behind those at the Golden Gate by 1.6 hours for high water and 2.2 hours for low water. The configuration of the system also affects the relative amplitude of the tides as well as tidal current velocities in various parts of the system.

The tidal lags and amplitude variations in the Bay system result in increased residence time of sediments in some parts of the system and decreased residence time in others, having the effect of increasing deposition in some areas and scour in others.

The tides of the San Francisco Bay system are of a semi-diurnal mixed type with two high and two low waters per day with a large diurnal inequality as shown in Figure 2. The largest difference in range is between higher high water (HHW) and the subsequent lower low water (LLW). The rise and fall of the tide modifies the effect of wave action on the bottom sediments (i.e., shallow sub-tidal zones of the Bay are exposed to greater wave turbulence during periods of low water than high water).



MEAN TIDE CURVE AT GOLDEN GATE
SAN FRANCISCO BAY



ELEVATION OF MEAN ANNUAL TIDAL STAGES

FIGURE 2 TIDAL TIDAL RANGES

The effect of the long ebb coupled with the greater range between HHW and LLW exposes a wide expanse of intertidal sediments to wave generated erosion, resuspension and transportation for an extended period of time. During this period of exposure to the atmosphere, the surface sediments in the intertidal mudflats are also subject to oxidation. The tidal prism of the entire Bay system has been calculated to be 1.5 billion cubic meters. This means that about one-fourth of the volume of the entire system (including Suisun Bay) moves in and out of the Golden Gate twice during each tidal day.

WAVES

Waves erode, resuspend and transport bottom material within the Bay system. Wave action is an especially effective force in the shallow areas of the Bay. Energy characteristics (height, length and period) of wind generated waves are determined by fetch, velocity, duration and direction of the wind, and by depth of water. The transmission of shallow water wave energy (depth of water is less than 1/2 wave length) is controlled and modified by submarine topography.

The effect of ocean waves and swell on sediment transportation in the estuary is minimal except near the mouth. This results from the damping effect of the narrow Golden Gate on waves and swell moving into the Gulf of the Farallones from offshore generating areas.

The predominant wind direction is from the west through south. These wave-producing forces coupled with a long fetch and duration can generate one meter high waves over broad reaches of the Bay. It is during this period that the greatest rate of annual shoaling appears to occur in certain regions of the Bay. The effective depths of wave action (wave base) in estuaries is generally limited to depth less than 9 meters below mean sea level. In the shallow subtidal areas wave turbulence erodes bottom sediments and resuspends the sediments into the water column. Sediment particles resuspended by wave action are transported in the direction of water mass transport. The progressive motion of orbiting water particles within waves traveling over shallow regions results in the slow shoreward advance of sediment in the direction of wave propagation. In the intertidal areas breaking waves churn up the sediment within the breaker zone and transport it shoreward in the wave of translation. At the shore, longshore transport is one of the primary mechanisms causing material to move laterally and accumulate in certain zones. This longshore transport is caused by the oblique approach of incoming waves and the redistribution of wave energy along a shoreline. The net effect of wave action in the Bay is the delivery of suspended and bedload sediment to the eastern shore of the Bay. This sediment is deposited to form extensive subtidal and intertidal mudflats.

CURRENTS

Current action in the San Francisco Bay system can be separated into tidal and non-tidal currents. Primary non-tidal currents include river inflow, wind-drift, and salinity-density currents. The tidal current regimen is a mixed type with four instances of slack water and four instances of maximum velocity during two floods and two ebbs daily. Highest current strengths are attained during the period of long ebb between higher high water and lower low water of the tidal cycle. Ebb currents are increased by freshwater outflow; conversely, flood currents are reduced by the same force.

Velocity and direction of tidal currents vary in the water column with depth, and direction depends on phasing of tide, freshwater inflow and submarine topography. During high freshwater inflow (winter conditions), ebb currents predominate at all depths. However, during low freshwater inflow (summer conditions) flood currents predominate at lower depths.

A longer period of low current velocities occurs around high water slack than during low water slack caused by a decrease in tidal wave amplitude towards the tidal flats along the Bay shore. Flood-tide waters advance in a uniform front, depositing material on the intertidal flats as they travel shoreward. Ebb-tide waters retreat in channels meandering across the intertidal flats, eroding material from the bed and banks of the channels as they move towards deeper water.

Tidal currents erode, resuspend (turbulent mixing) and transport sediment from the up-current sediment reservoirs of Suisun and San Pablo Bays. This sediment is moved in suspension and as bedload through Carquinez and San Pablo Straits into Central San Francisco Bay.

Once these sediment-laden waters arrive in the broad expanses of Central Bay, their velocity is diminished and they lose much of their ability to carry sediment. At the same time these brackish waters are mixed with more saline ocean waters, and suspended sediments floc and settle to the bottom. These newly arrived sediments are subject to movement by additional estuarine processes.

Freshwater inflow during winter storm runoff transports sediment through North and Central Bays and the Golden Gate, dispersing the sediment charged waters into the Gulf of the Farallones. Sediment is transported in suspension and dragged along the bottom as bedload. During the wet season, high volume/velocity river currents are especially effective in eroding, resuspending and flushing unconsolidated sediments from the Bay floor. Sediment temporarily settles during calms between winter storms.

Freshwater inflow is diluted as it mixes with saline water in the Bay. This results in horizontal and vertical salinity gradients. These gradients are greatest during winter freshets. Density-salinity currents move up-Bay along the Bay floor displacing less saline waters moving towards the Golden Gate in the upper water column. This saltwater wedge (vertical salinity stratification) is strong enough to erode and to transport sediment in the near bottom strata of the water column. Average speed of this near bottom current between the Gulf of the Farallones and San Pablo Bay has been calculated to be 4 kilometers per day. Because this current is density driven, it is able to transport sediment in the deeper parts of natural channels and in areas deepened by dredging. Density-driven salinity currents supplement flood-tide bottom filling of tranquil, maintained waterways. These currents reinforce the tidal regime in San Francisco Bay, generating a pattern of bottom strata filling and upper strata emptying of the tidal prism. The interface between the fresh and salt water masses is a zone of vertical mixing and flocculation of colloidal sediments. This collision of water masses results in sediment deposition along the bottom beneath the shifting salt water wedge interface. The deposition process occurs in the Suisun Bay and Carquinez Strait region of the Bay.

The prevailing wind forces over the Bay produce two distinct wind-drift currents. Velocities of wind-drift currents in estuaries reach 2-5 percent of the wind force. Strong westerly summer winds produce easterly setting currents. These currents drive sediment-bearing surface waters across the open water reaches of the Bay and pile water up along the shore (wind set-up). Winter winds blow predominantly from north-northeast which increase the competency of freshet and tidal flows to flush out unconsolidated sediments from North and Central Bays. This offshore wind pattern is frequently interrupted by violent southeast gales associated with low pressure systems passing west to east over the Bay area. Southeasterly winter gales are generally of short duration and generate very temporary north -setting currents.

The University of California conducted a comprehensive study of San Francisco Bay from July 1960 to July 1964 in which the Bay's hydrologic system was characterized (1). The researchers found that the mean annual rates of total advective flow during the survey period were -2 and +568 cubic meters per second in the southern and northern reaches of the Bay, respectively. The maximum observed positive and negative monthly flow rates were 63 and -37 cubic meters per second in the southern reach and 2,872 and -14 in the northern reach. The southern reach is generally a neutral arm because of the relatively insignificant advective flow in the region. The northern arm, however, is a significantly positive system as a result of the Delta outflow. From Corps studies the mean annual tidal prism of the southern reach was about 8.5 $x\ 10^8$ cubic meters. This value is about thirty percent greater than the number of cubic meters determined for the northern reach. Using tidal wave amplitudes, amplitude time lags, and phase shifts, the tidal wave is determined to be predominantly a standing wave in the southern arm and a progressive wave undergoing extensive frictional decay in the northern arm. The magnitude of the advective flows significantly influences the characteristics of this northern tidal wave.

The degree of turbulence in an estuary dictates the distribution of water properties. Estuarine mixing structure has been classified in terms of salinity as (a) vertically mixed or well-mixed, (b) slightly stratified or partially mixed, and (c) highly stratified. For low freshwater inflows (140 to 280 cubic meters per second), all portions of the Bay system are classified as well mixed. For inflows of 2,830 cubic meters per second, the Golden Gate and extreme South Bay areas remain well-mixed, but mid-South Bay, San Pablo Strait and Carquinez Strait change to a partly mixed condition. In the area above Carquinez Strait the flow is highly stratified. For an inflow of 5,660 cubic meters per second, there is no evidence of a well-mixed condition anywhere in the Bay system. A major part of the system is partly mixed and a highly stratified condition extends far downstream from the head of Suisun Bay to and beyond Carquinez Strait. Thus, the San Francisco Bay system is not a single well-defined body of water.

For this study the Bay was delineated as a series of four significantly different sub-bays: (1) South Bay, (2) Central Bay, (3) San Pablo Bay, and (4) Suisun Bay. These sub-bays differ from one another in their water characteristics because of many diverse factors including tidal influence, current patterns, freshwater inflow and human activity. Ranges of the basic water quality parameters are listed in Table 3.

TABLE 3

WATER QUALITY 1970-1975

PARAMETER		SOUTH BAY	CENTRAL BAY	SAN PABLO	SUISUN BAY
SALINITY	max	30.0	30.5	23.5	-
(ppt)	min	18.0	18.0	1.5	-
	mean	23.7	24.5	11.5	-
TEMPERATURE	max	19.5	19.8	20.0	26.0*
(°C)	min	10.9	10.0	9.8	6.0*
	mean	14.5	14.4	14.4	16.6*
DIS. OXYGEN	max	9.3	9.0	10.2	11.8*
(mg/1)	min	6.5	6.6	6.7	6.8*
	mean	7.9	7.9	8.6	9.4*
pH	max	8.2	8.0	8.0	8.6*
(Std. Units)	min	6.9	7.3	7.3	6.8*
	mean	7.7	7.7	7.7	7.7*
SUS. SLDS.	max	-	47*	1[illegible]3*	245*
(mg/1)	min	-	26*	33*	11*
	mean	-	36*	77*	82*
TRANSPARENCY	max	1.2*	1.6*	-	0.2*
(feet)	min	0.2*	0.9*	-	0.2*
	mean	0.7*	1.3*	-	0.2*
TURBIDITY	max	45	24.0	390	140*
(NU & FTU*)	min	1	5.0	10	17*
	mean	20	14	129	52*

* FROM EPA STORET SYSTEM; ALL OTHERS FROM STANFORD RESEARCH INSTITUTE SURVEY (Biological Community, Appendix D).

BAY SEDIMENTS

Geological formations in and adjacent to the San Francisco Bay are principally alluvial formations ranging in age from mid-Pleistocene to Recent. Sediments deposited within the Bay are very soft to firm clay with varying amounts of silt, sand, and carbonaceous material. Bay sediments have been classified as Older Bay Mud Formation, Sand Deposits and Younger Bay Mud Formation.

With the exception of the sandy sediments associated with the San Francisco Bar Channel, Southhampton Shoal, Pinole Shoal and Suisun Bay, maintenance dredging operations in San Francisco Bay move "Younger Bay Mud." The consistency is shown in Figure 3 with the mud entering the hopper. Bay mud consists of soft, plastic, black-to-grey silty clay or clayey silt with minor organic material and clayey fine-grained sand which has been deposited in the Bay largely by flocculation. Flocculation occurs when the suspended clay and colloidal particles interact with the salt water to aggregate, and then settle out of the water column. A typical comparison of the actual grain size (dispersed) versus the effective grain size in the estuarine system (non-dispersed) is shown in Table 4. The data in the table are based on single samples and do not necessarily represent the project areas as a whole.

FIGURE 3 BAY MUD DURING DREDGING

TABLE 4

PHYSICAL PROPERTIES OF BAY SEDIMENTS

Physical Properties	Mare Island Strait	Oakland Outer Harbor	Oakland Inner Harbor
Dispersed Grain Size			
% Sand (>0.074 mm)	12	5	15
% Silt	46	39	37
% Clay (<0.002 mm)	42	56	48
Non-dispersed Grain Size			
% Sand (>0.074 mm)	13	17	20
% Silt	87	83	75
% Clay (<0.002 mm)	0	0	5
Organic Carbon (%)	1.56	1.28	1.62
In-place Density (g/ml)	1.30	1.43	-
Water Content (%)	102	124	-

Bay mud tends to flow and has very little bearing strength. It is easily resuspended by wind-wave action, freshet and tidal currents. These characteristics of Bay mud result in a very dynamic system with sediment recirculation through scoured channels and on and off extensive mudflats. The properties of Bay mud can be explained by its high water content and low in-place density. The net weight is about 1.3-1.4 grams per milliliter and more than forty percent moisture. The clay size particles make up from 40-90 percent of the material, and peaty or lignitic material is five percent. The clay size fraction is composed of one-third montmorillinite, one-third normal and hydrated mica, and one-third mixed-layered montmorillinite, chloritic and kaolinitic materials.

Sedimentation within the San Francisco Bay system has been estimated in several different studies. These studies have produced varying estimates of inflow-outflow and distribution volumes in the Bay system. The variance can be attributed to paucity of data available to investigators at the time of each study.

Smith (2), using U.S. Coast and Geodetic Survey surveys of the Bay and logs of borings, estimated the total deposit of Bay sediments to be 12.2 billion cubic meters. The deposits were lightest in Suisun Bay, heaviest in Central Bay and roughly the same for the remaining areas. The ratio of deposition per unit area is 1:3:2 for Suisun Bay, Central Bay and Carquinez Strait, San Pablo Bay and South Bay, respectively. Generally, these areas have experienced cycles of deposition and erosion, with the greatest deposition taking place during the hydraulic mining era in the Sierra Nevadas. Gilbert (3) estimated that just during the period of 1850-1914, 1.2 billion cubic meters of sediment were deposited in the Bay system.

Two other factors affecting the annual sedimentation in the Bay system are annual dredging and disposal operations and resuspension of bottom sediments due to wind-generated turbulence and tidal currents. Approximately 7.6 million cubic meters of Bay sediment are dredged annually by the Federal Government and private concerns in the Bay system. Most of this sediment is released into the Bay waters at one of four disposal sites. Assuming that these sites received dredged sediments over a 250-day period and that the material disperses over a 260-square-kilometer area, 120 cubic meters of dredge material would be placed in suspension per square kilometer per day of dredging. In contrast, Krone (4) estimated the amount of material suspended by wave action in a square kilometer of shallow area by conservatively using an average suspended sediment concentration of 0.5 grams per liter over a 1.5 meter water depth when the wind blows over 10 knots. Krone estimated that each square kilometer of shallow area suspends 770 metric tons of sediments per day. Using 0.4 grams of sediment per cubic centimeter, a total of 1,900 cubic meters per square kilometer per day is resuspended by wind-driven waves. Figure 4 is a summary of the various estimates of sedimentation in San Francisco Bay (Appendix B).

Sediment deposition in the Bay system depends on local circulation conditions, type of accumulation processes, and physical characteristics of sediment particles, as well as concentration and availability of suspended and bedload material. Sediment deposition patterns reflect the energy gradient formed by dynamic estuarine forces within the Bay. Suspended and bedload sediment is transported from high energy areas to low energy areas. Suspended and bedload concentration is directly proportional to transportation energy, if the available sediment supply is not a limiting factor. Wave action and current velocity are the dynamic mechanisms controlling sediment transportation. Therefore deposition zones are situated in tranquil areas where the energy of these forces is dissipated or nonexistent. Suspended sediments settle to the Bay floor as a result of gravity force in these quiescent accumulation zones.

The effective grain size is the non-dispersed grain size (because of flocculation in salt water) and is shown in Table 4. Without flocculation, a large portion of the sediments (fine silts and clays) would

remain suspended in the water column. As the sediments aggregate and concentrate in the lower water column, the rate of settling decreases because of particles interfering with one another. This phenomenon is referred to as "hindered settling" and results in the establishment of a fluff zone, a density transition zone between the water column and the consolidated bottom. In San Francisco Bay, the fluff condition more commonly occurs and is more persistent in dredged channels than disposal areas because of the differences in current energy and configuration.

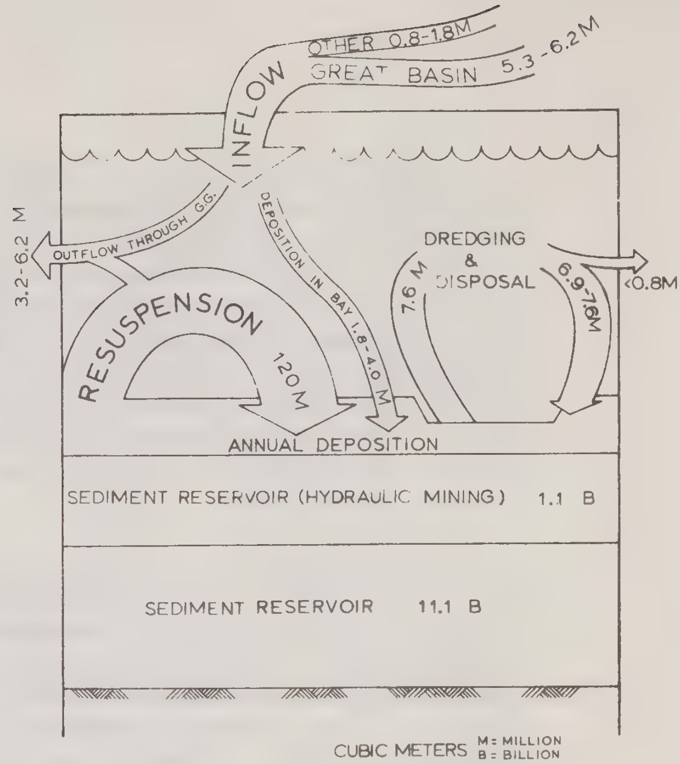


FIGURE 4 SEDIMENT MOVEMENT IN SAN FRANCISCO BAY

CONTAMINANTS

Contaminants enter the San Francisco Bay system through natural weathering processes of rocks and soils and by anthropogenic means on land, air and water. The estuary is a sink or settling basin for all upstream discharges or discharges directly into the estuary. Contaminant concentrations depend on the estuary's ability to assimilate or disperse the contaminants.

Solid waste substances and dissolved waste materials are introduced in suspended form into the Bay. Contaminants enter the Bay system directly via municipal sewage and industrial waste outfalls, storm drains and surface runoff, aerial fallout, overboard discharge from vessels, and enter indirectly via rivers and streams conveying agricultural drainage and materials from upland erosion to the Bay, and via leaching from waste disposal sites located adjacent to the Bay and its tributaries. Dissolved substances are sorbed by particulate matter both before entry and after entry into the estuary. These organic and inorganic contaminants show behavior and distribution patterns similar to that of natural sediments with the physical setting and estuarine processes responsible for their movement and deposition. Contaminated sediments accumulate in certain deposition zones within the Bay system.

Contaminant samples have been obtained by the Corps of Engineers for all active maintenance dredging projects since 1970. In addition, contaminant samples are taken for all proposed navigation projects during feasibility studies. Table 5 is a summary of mean contaminant concentrations based on all Corps samples in the Bay from 1970 through 1974. The number of samples for dredged channels range from 500 to over 800 samples.

TABLE 5

MEAN CONTAMINANT CONCENTRATIONS

	LEAD ppm	ZINC ppm	MERCURY ppm	CADMIUM ppm	COPPER ppm	OIL & GREASE ppm	VOLATILE SOLIDS ppm x 10^4	COD ppm x 10^4	TKN ppm
NORTH SAN FRANCISCO BAY									
DREDGED CHANNELS	38.8	126.1	0.41	2.54	85.0	700	6.09	4.10	900
PINOLE SHOAL	20.4	72.3	0.29	----	----	400	5.11	3.02	900
NAPA RIVER	21.6	86.3	0.33	----	----	700	6.06	4.03	1500
SONOMA CREEK	30.4	95.8	0.40	----	----	1000	7.59	6.42	2200
PETALUMA RIVER	41.2	112.0	0.57	1.69	----	900	6.62	4.07	1300
POINT DAVIS	33.7	87.9	0.28	----	----	300	3.69	2.03	800
MARE ISLAND STRAIT	58.8	193.3	0.56	2.69	85.0	800	7.99	5.21	800
CARQUINEZ STRAIT & SUISUN BAY	26.7	72.7	0.21	----	----	500	5.41	4.35	900
UNDREDGED AREAS	37.2	111.4	0.75	0.75	34.3	500	5.88	3.30	1100
CENTRAL SAN FRANCISCO BAY									
DREDGED CHANNELS	33.3	101.6	0.62	1.70	35.7	800	6.06	4.33	1050
WEST RICHMOND CHANNEL	16.7	55.3	0.31	0.56	20.2	100	3.39	2.14	400
SOUTHHAMPTON SHOAL	15.7	54.5	0.38	0.86	25.3	200	5.39	2.58	700
RICHMOND OUTER HARBOR	28.3	98.0	0.46	1.24	48.6	600	5.68	4.19	1000
RICHMOND LONG WHARF	29.6	104.3	0.53	1.01	50.0	700	6.61	3.93	1400
RICHMOND INNER HARBOR	23.9	90.9	0.40	1.69	49.7	500	5.95	4.37	1200
SAUSALITO	16.8	80.0	0.55	0.98	19.2	----	----	4.98	----
OAKLAND OUTER HARBOR	49.3	136.1	0.46	1.45	35.7	1400	6.20	3.99	1350
OAKLAND INNER HARBOR	58.3	141.3	1.05	1.62	----	650	4.38	3.89	780
ALAMEDA NAVAL AIR STA.	49.3	131.7	1.05	1.82	53.0	1350	6.94	5.16	1600
ISLAIS CREEK	30.9	62.9	0.84	2.30	19.3	500	----	3.13	1300
UNDREDGED AREAS	21.4	110.1	0.70	0.95	39.7	400	5.61	3.44	1000
ALL DREDGED CHANNELS	35.5	108.1	0.55	1.59	41.6	800	6.03	4.12	1000
ALL UNDREDGED AREAS	34.3	110.1	0.71	0.86	36.2	500	5.65	3.30	1000

Generally, dredged channels in North San Francisco Bay have higher levels of lead, zinc, cadmium, copper and volatile solids than channels in Central San Francisco Bay. Dredged channels of Central Bay have higher levels of mercury, oil-grease, chemical oxygen demand and total Kjeldahl nitrogen. Undredged areas of North and Central Bay on the whole have lower levels of these contaminants. Some contaminants such as zinc, mercury, oil-grease, and total Kjeldahl nitrogen can be found at higher levels outside dredged channels.

Contaminant levels are generally associated with sediment type (particle size) which is reflected in both vertical and horizontal distribution of contaminants. However, this relationship is not absolute and other factors such as proximity to the source of contaminants, rate of shoaling of contaminated sediments, rate of contaminant input, and association of contaminants with other parameters such as organics most probably play a role in this distribution.

Particle size characteristics of sedimentary deposits in the Bay vary greatly both vertically with depth and spatially over area. Sediments range from a homogeneous silty clay with less than one percent sand to alternating layers of clayey silt and silty sand. Physical characteristics of sedimentary deposits reflect the environment of deposition. The environment of deposition is determined by processes mentioned previously, e.g., tide and tidal currents, water circulation and mixing characteristics, and wind-wave action. Where sediments are found to be uniformly distributed, the environment of deposition has necessarily been continuous throughout the history of deposition. Conversely, where the sediments exhibit a heterogeneous distribution the environment of deposition has not been continuous. The changing environment of deposition is reflected by the vertical changes in the character of the sedimentary deposits. Furthermore, relative magnitude (energy input) of physical processes that make up the environment of deposition may be determined by size and distribution characteristics of sediments. Thus, uniformly distributed fine sedimentary deposits indicate a continual low transporting energy environment, whereas a continuous high transporting environment would result in uniformly distributed coarse sediments.

Highest contaminant levels in San Francisco Bay are normally associated with the finest sediments. Zinc is shown as an example in Figure 5. Where particle size of sediment varies widely with depth or area, contaminant levels also differ greatly. Figure 6 is an example of spatial distribution of zinc and median particle size in surface sediments of San Pablo Bay. General distribution of zinc and median particle size indicates the importance of the environment of deposition. In the case of Figure 6, currents appear to be the primary process for distribution. Highest current energy areas in San Pablo Bay are located

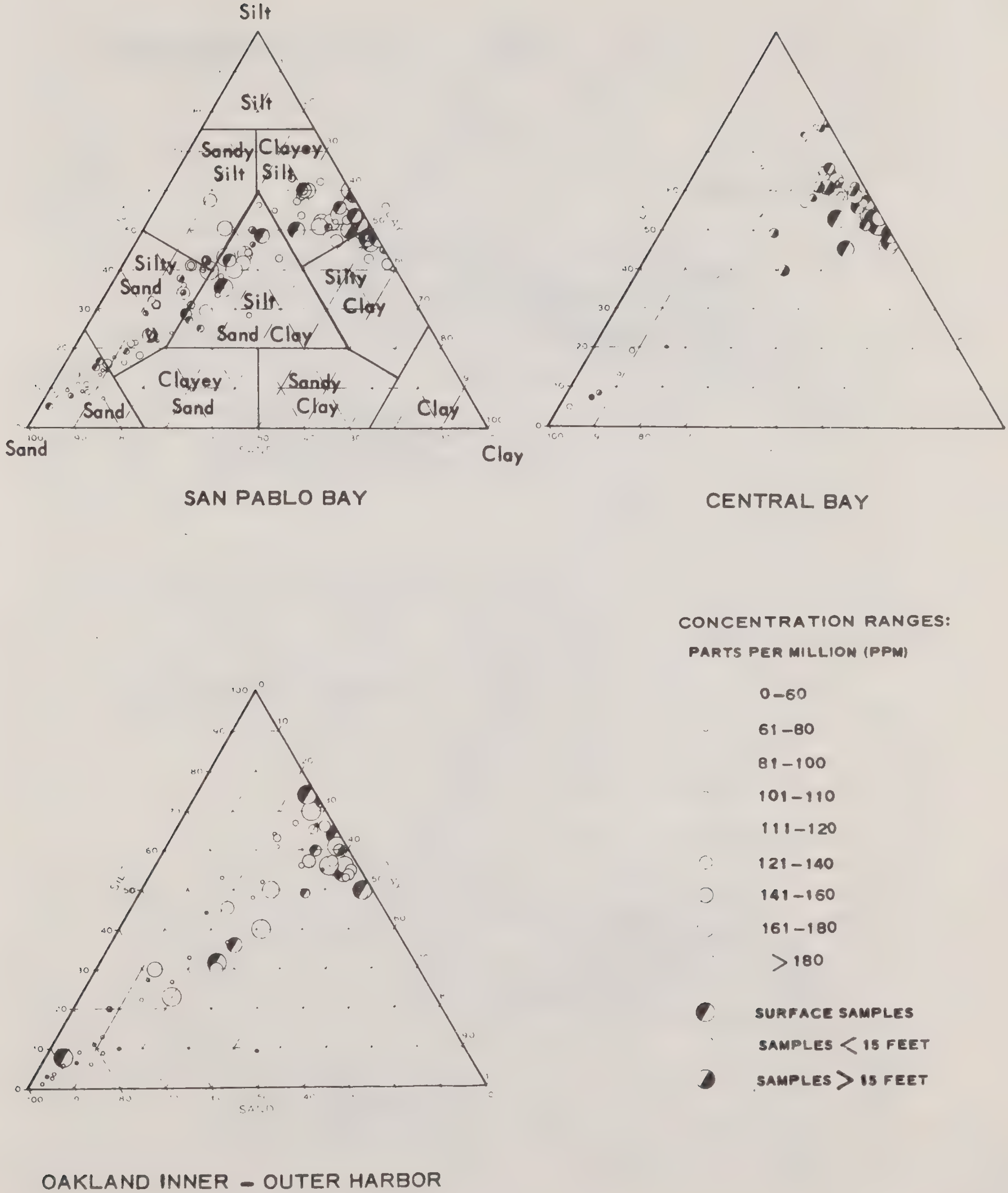


FIGURE 5 TRILINEAR GRAIN SIZE-CONTAMINANT RELATIONSHIPS: ZINC

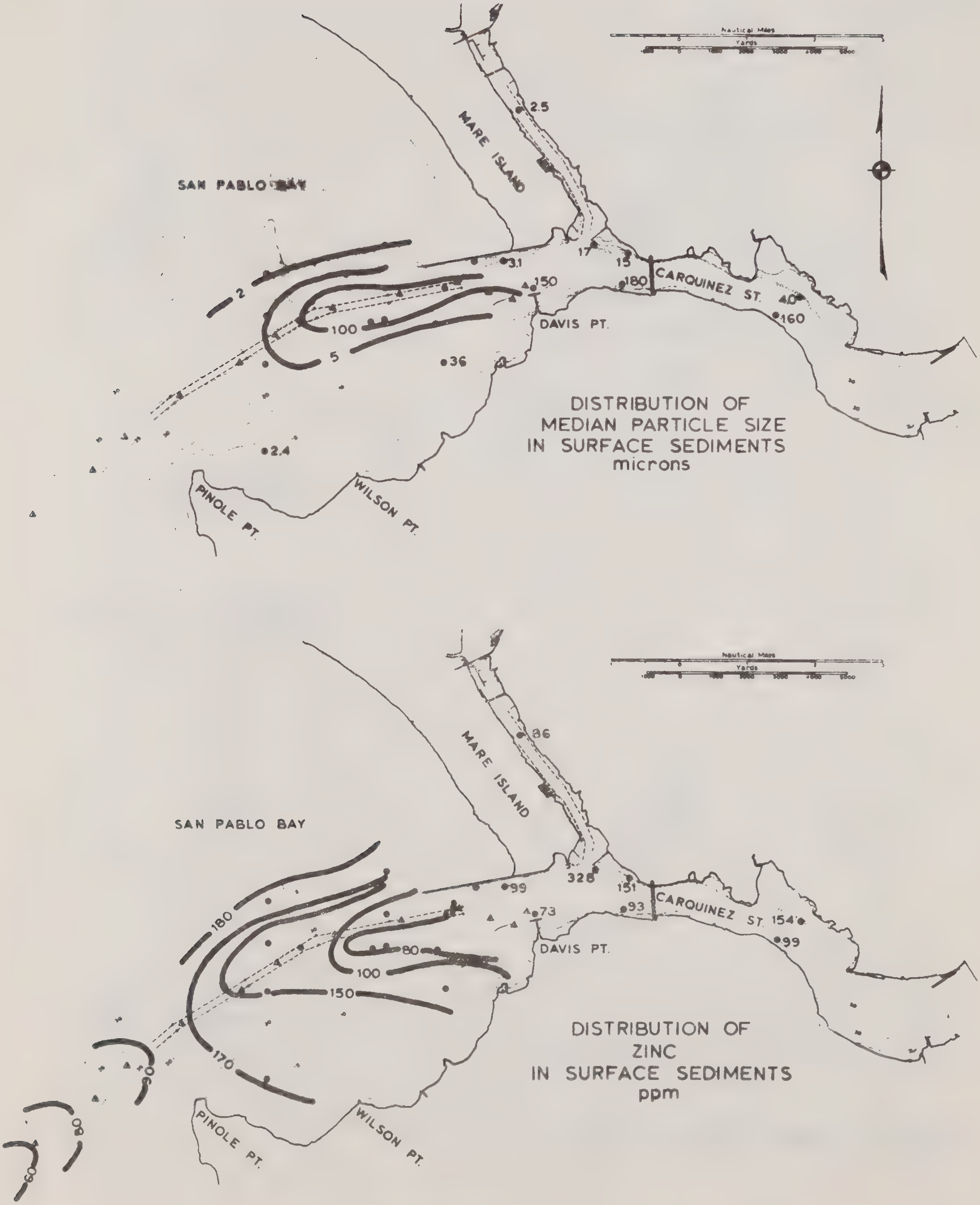


FIGURE 6 SURFACE DISTRIBUTION OF PARTICLE SIZE AND ZINC

in the natural channel and maintained navigation channel (indicated on Figure 6 as dashed lines). Moving towards the flanks of the natural channel the current energy decreases. In a similar manner, moving to the west away from the confines of Carquinez Strait current energy also decreases. Distribution of zinc (as well as other contaminants) and particle size of sediments closely reflects the current energy gradient. Highest zinc levels and finest sediments are found on the shallows, adjacent to the natural channel where current velocities are lowest. Zinc levels also increase and sediment particle size becomes smaller in a westward direction as current energy decreases.

Vertical distributions of contaminants in sediments of San Francisco Bay show similar patterns to that shown in Figure 6, but generally reflect historical changes in the environment of deposition. The Bay can generally be broken down into five units in regard to sediment-contaminant relationships. These areas are as follows: (1) enclosed water bodies, (2) shallow protected open water bodies, (3) shallow exposed open water bodies, (4) natural channel margins, and (5) natural channels.

The enclosed bodies of water which include most harbor complexes in San Francisco Bay are typically low energy environment areas with low velocity currents and very little wind-wave action. Sedimentation in these areas is moderate to high. The sediments are generally very fine and uniformly distributed with depth. Sediments contain very little sand and have high percentages of clay. Consequently, contaminant levels in sediments of these areas are very high. In some areas under this category relic sand deposits may be found; however, once these coarser, less contaminated sediments are removed by dredging, new shoaling sediments will be comprised of a fine, more contaminated material.

The shallow protected open bodies of water of San Francisco Bay are very similar in sediment and contaminant characteristics to the enclosed water bodies. These areas are located in partially protected areas where wind-wave action is subdued and where current velocities are very small. These areas are found along the leeshore of the Bay or along extensive sub-tidal flats. The sub-tidal flats off Corte Madera and San Rafael, and the northern and southern shallows of San Pablo Bay are included in this category. These are low to moderate energy environment areas and sediments are correspondingly very fine. Sediments are uniformly distributed with depth and have a very low sand content and high clay content. Average sedimentation rates in shallow protected areas are low to moderate; however, large seasonal fluctuations may occur. Contaminant levels in the shallow, protected areas are high and often exceed levels in enclosed water bodies. Contaminants are very often uniformly distributed with depth.

The shallow, exposed open bodies of water of San Francisco Bay are geographically similar to the shallow protected areas. However, these areas experience greater wind-wave action and stronger current velocities. Consequently, the moderate energy environment predominates and sediments are somewhat more coarse. Berkeley Flats is an example of a shallow exposed area. Sedimentation rates on Berkeley Flats are low to moderate. Wave action suspends the fine clays and currents transport them out of the area so that silt-size sediments predominate. Contaminant levels in these sediments are fairly low and are fairly uniformly distributed with depth.

The margins of the natural channels of San Francisco Bay are comprised of the most heterogeneous sediments found in the Bay. Sediments range from silty sand to clayey silt material with much interbedding, indicating a fluctuating moderate to high energy environment. These channel margins have historically shown the highest rates of sedimentation in the Bay. Contaminant levels in these areas also show large vertical fluctuations.

The natural channels of San Francisco Bay have the highest transporting energy environment of the Bay. Historically, these channels have shown very little sedimentation and in many cases have shown erosion. Because of the high energy environment, sediments are coarse and contaminant levels are low. These channels are located in water depths of greater than 25 feet in San Francisco Bay.

BAY BIOTA

The San Francisco Bay system contains the wealthiest fisheries resource along the California coast. The configuration of the Bay, its size, mixing characteristics, and supply of nutrient-rich waters from the Delta all lend to this wealth and to its great diversity of the natural resources.

These diverse resources range from anadromous fish to salt marsh biota with each forming an integral part of the Bay's estuarine ecosystem. The ecosystem is too complex to be easily described holistically, so for descriptive purposes it has been artificially divided into six broad habitats. Although each habitat has many unique characteristics, none functions independently but all are inextricably interrelated and affect one another. The habitat categories are: (1) diked salt ponds, (2) marshes, (3) fouling areas, (4) tidal flats, (5) benthic and (6) pelagic domains. The latter two categories can be further sub-divided. The benthic habitat incorporates the organisms living in the mud (infauna) and those living on the mud's surface (epifauna). The pelagic habitat

includes those organisms in the water column which are drifting or free-floating (plankton) and those which are actively motile or free-swimming (nekton). The distribution of these habitats in the Bay system ranges from the margins to the open-water areas and is pictorially displayed in Figure 7. A brief description of each habitat follows.

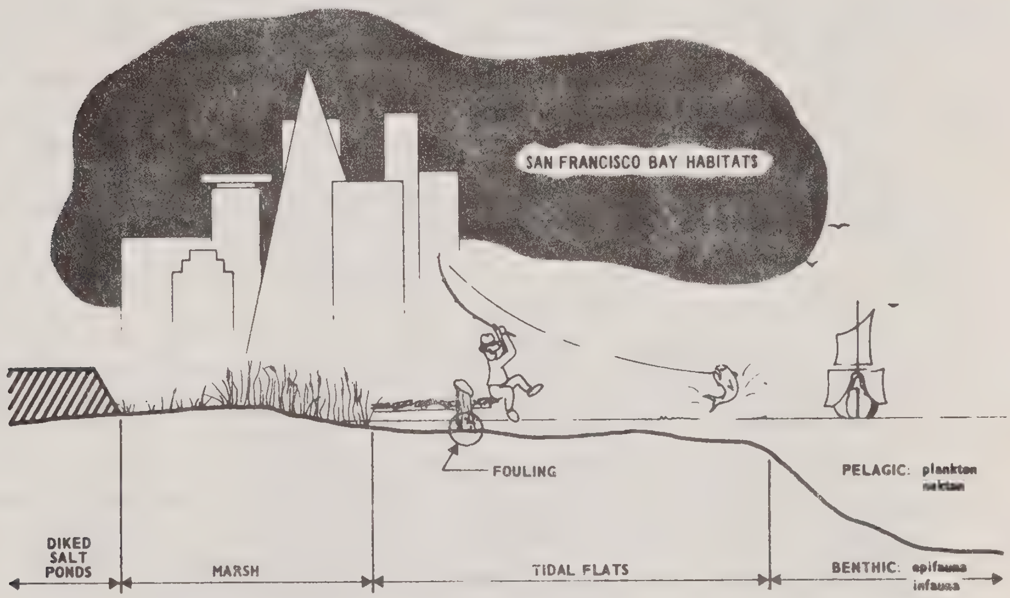


FIGURE 7 BAY HABITATS

(1) <u>Diked Salt Ponds</u>. Salt evaporation ponds are situated primarily in the southern reach of South Bay and around San Pablo Bay. These ponds are primarily held by the Leslie Salt Company and occupy an area in excess of 16.0 square kilometers. They provide a unique environment for those plants and animals that can adapt to relatively high salinity and temperature ranges, and variable oxygen levels.

In terms of primary productivity, the annual production of <u>Stichococus bacillaris</u>, a common green alga in the Alviso salt ponds, has been calculated to be about 14.6 metric tons of organic matter per hectare. This is quite remarkable when compared to the estimated annual production rate of an estuarine zone (11 to 22 metric tons per hectare) or a coastal zone (2.2 to 3.4 metric tons per hectare). However, because of the diking of the ponds, only a relatively small percentage of this productivity enters the foodweb of the Bay ecosystem as compared to the percentage contributed by undiked marshes or tidal flats.

In addition to algae, the salt ponds support many other forms of life. Of particular importance are the number and variety of birds that forage in the ponds. Comparisons of bird densities between salt ponds and tidal flats indicate that more than twice the number of birds per unit area can be found in the ponds (approximately 160 birds versus 75 birds per hectare). Among the general types of birds making heavy use of the ponds are shorebirds, ducks, grebes and gulls. The salt evaporation ponds, although manmade and having displaced many hectares of marsh and tidal flat, have become an important habitat and an integral part of the environment of the Bay.

(2) Marshes. Until recently, marshlands bordering the coastal bays and estuaries of the United States were considered by some to be "wastelands." Marshlands were prime targets for reclamation, succumbing to agricultural, industrial and urban sprawl. Only recently has there been widespread recognition of the critical value of wetlands as feeding and nursery areas for fish and wildlife, as a source of energy (food) and oxygen for marine consumers, as sinks for nutrient and toxic pollutants, and as stabilizers of eroding shorelines.

In general, only areas above the mean tide level are colonized by vascular plant life. In San Francisco Bay there are two dominant vegetative zones within this area above mean tidal level and the highest high water mark. They are the Spartinetium (consisting of genetic varients of California cordgrass) and the Salicornietium (consisting of genetic variants of pickleweed). Typically the Spartinetium lies between the mean tide level and mean high water. The Salicornietium lies above mean high water and continues in saline soils above the estimated highest tide.

The Spartinetium intertidal plant community is named for its dominant plant variety, California cordgrass (*Spartina foliosa*). The cordgrass zone represents the frontier of intertidal colonization by phanerogams (seed producing plants). Cordgrass is uniquely adapted to withstand the stresses of regular tidal inundation, erosion and fluctuating salinities. It possesses an abundance of air storage and conduction tissue (aerenchyma). It also utilizes a glandular apparatus

(hydathodes) which actively secretes salt allowing the plant to tolerate high salinities. No other local plants display its unique abilities and, consequently, the Spartinetium is typically represented in the Bay by pure homogeneous stands of this single species.

Similarly the Salicornietium is named after the dominant plant variety, pickleweed (Salicornia pacifica). Unlike cordgrass, pickleweed does not have the abundance of aerenchyma tissue for the storage of oxygen for respiration during long periods of submergence. Thus, pickleweed will be found dominant only above the mean of the high waters where submergence occurs on the average of only once per day. In these higher areas of the intertidal zone, evaporation causes higher soil salinities than found in the lower intertidal substrates. Pickeweed's ability to withstand high salinities is its greatest asset. It is virtually without a floral competitor along the shores in soils with salinities between 35 ppt and 80 ppt. In the part of the Salicornietium where salinity is not so extreme, several other intertidal and near intertidal plants may be found such as salt grass (Distichlis spicata), jaumea (Jaumea carnosa) and alkali heath (Frankenia grandifolia).

Marshlands are utilized as feeding and nursery areas by many fishes found in the Bay. The sloughs of the Suisun marsh are nursery areas for many important sport fishes including striped bass (Morone saxatilis), King salmon (Oncorhynchus tshawyscha) and white catfish (Ictalurus catus). Many non-game fish species, such as carps, suckers, crappies and sculpins, also depend on sloughs for shelter and food.

Many species of water birds and several mammalian species use marshlands for nesting, feeding and/or resting. In addition, many non-water birds, such as song birds, hawks and owls inhabit the tidal marshes of the bay, either as residents or winter visitors.

(3) Fouling. The fouling community is a highly productive community found on local wharf, pilings, boat floats and boats. While the piling may look to be composed of barnacles and mussels, living within this community are 25 to 50 species of marcroscopic organisms composed of 10,000 to 100,000 specimens per square meter of surface of crustaceans, clams, snails, limpets, algae, worms, etc., especially during the summer. Most of these infaunal organisms have very short like cycles, hence they contribute a great deal to the biomass.

One of the most common of the organisms found on either exposed or protected pilings is the barnacle Balanus gladula. Intermingled with these barnacles and a little below them is the mussel community. The bay mussel (Mytilus edulis) sometimes grows in great bunches completely surrounding a pile. Among the mussel clusters are a myriad of organisms including hydroids, isopods, tunicates, algae, etc.

The members of the community most important to man are the borers which are both common and destructive. For many years the Bay has had some protection from the boring isopod, Limnoria, and the shipworm, Teredo, because of pollution and freshwater inflow. But as the water quality of the Bay improves and more and more freshwater is diverted to Southern California, the damage from these organisms is expected to increase.

(4) Tidal flat. The tidal flat habitat is the open (non-marsh), shallow, intertidal region bordering the Bay and is actually an extension of the subtidal benthic habitat. The separation has been made here for descriptive purposes. In the Bay, there are approximately 18,000 hectares of tidal flat habitat. Its importance stems from both the plant and animal life it supports.

The production of basic organic nutrients vital to most types of life in an estuary is mostly associated with the plant life floating in the open water environment and with the marshes. Tidal flats, however, are also productive, having a unique population of photosynthetic organisms commonly known as benthic diatoms. These golden-brown, single-celled plants inhabit the flats in astronomical numbers and often give the surface of the flat a golden-brown tinge noticeable at low tide. While some species of benthic diatoms are sessile, others are able to migrate through the sediments (the first few centimeters) and absorb the necessary nutrients attached to clay particles or found in the interstitial waters between the sediment particles. These microscopic plants normally dominate the algal types on a healthy tidal flat. Other tidal flat algae in the Bay are bluegreens, and multi-cellular reds and greens. Ulva, Enteromorpha, and other green algae are commonly seen scattered along the flat during low tide.

Animals of the tidal flats are also numerous and among the various animals living in and on the flats, feeding on benthic diatoms and/or other matter are: roundworms (nematodes); ribbon worms (nemerteans); segmented worms (annelids); amphipods; the familiar shore crabs and young Dungeness crabs (market crabs); hermit crabs; barnacles, which are attached to solid objects such as old tires, boxes, rocks and seaweeds; bivalves; snails; and even small fish that live commensally in the burrows of certain burrowing animals. The distribution pattern of these animals on a given tidal flat depends on many environmental factors. Some of the factors affecting distribution of species include degree of low tide exposure, variations in temperature and levels of oxygen in the sediments.

Clam beds are highly characteristic of tidal flats, and these beds are so numerous in certain shallow reaches of the Bay that, if clams were not considered a health hazard to eat, San Francisco Bay would support the most important shellfishery along the California coast. At one time, an important shellfishery did exist in the Bay. The large bivalve resource is one important reason why the San Francisco shallows sustain such a tremendous population of shore birds and ducks.

The more typical known fishes that forage on the tidal flats during high tide but normally reside in deeper water are: sharks (brown smoothhound, lepard shark, spiny dogfish), skates and rays (bay ray, big skate, others), plainfin midshipman, bay pipefish, surfperches (shiner surfperch, pile surfperch, barred surfperch, others), gobies (tidewater goby, cheekspot goby, longjaw mudsucker, others) sculpins (staghorn sculpin, buffalo sculpin, cabezon, others), brown rockfish, flatfishes (English sole, Pacific sanddab, California halibut, starry flounder, others) as well as many other species of fish.

Waterfowl and shorebirds are also inextricably bound to the tidal flats because of the diversity of food available, such as large numbers of worms, snails, clams and mussels. Tidal flats host herons, egrets, plovers, avocets, stilts and probing shorebirds. These same birds are not normally found in the open water areas. Others frequent both the tidal flats and open water such as gulls, certain dabbling ducks, Canvasback and the American coot.

(5) Benthos. The benthos category is the largest of the six habitats in area. Not only are organisms found living in the mud (infauna) but various organisms move across or live on its surface (epifauna).

A benthic survey was conducted during 1973-74 to examine numerical and seasonal fluctuations of infauna populations of selected areas of the Bay (Appendix D). Eleven stations were located at seven sites in the Bay, three dredged channels and four disposal sites. The data are summarized in Table 6. The survey enumerated over 340 bottom species in the Bay (west of Carquinez Strait) with 41 species constituting the greatest number of individuals.

TABLE 6

CONCENTRATION OF MOST ABUNDANT BENTHIC ORGANISMS

Percentage of Population*

MARE ISLAND STRAIT Dredged Channel

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nematoda	4.9%	0.18	9.34	1.97	0.74	3.16
Oligochaeta	87.3	0.22	262.78	8.38	0.35	6.70
Arthropoda						
Copepoda	5.7	2.38	3.96	9.03	0.51	10.78
Total	97.9%	2.78	276.08	19.38	1.60	10.64
All organisms+	100.0	3.30	280.07	20.32	1.70	11.33

CARQUINEZ STRAIT Disposal Site

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nematoda	16.4%	0.17	1.43	0.84	1.45	41.40
Oligochaeta	65.9	1.00	12.28	26.36	6.63	134.44
Polychaeta						
S. benedicti	8.8	0.13	2.63	14.61	0.04	5.92
Arthropoda						
B. improvisus	2.9	0	7.81	0	0	0
Mollusca						
M. arenaria	1.6	0.74	0.70	0.31	2.47	0.16
M. balthica	1.7	0.68	0.32	0.19	0	3.10
Total	97.3%	2.72	25.17	42.31	10.59	185.02
All organisms+	100.0	3.62	26.70	44.21	11.76	166.21

ALCATRAZ Disposal Site

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nemertea	1.8%	0	9.87	1.07	0	0.82
Nematoda	4.1	0	22.04	2.86	0.07	2.30
Oligochaeta	1.3	0	6.27	1.79	0.03	0.70
Polychaeta						
Hesionura sp.	69.6	0	457.73	0.51	0	7.78
Syllides sp.	8.4	0	56.22	0.04	0	0
Streptosyllis sp.	7.2	0	0	0.17	0	44.69
Arthropoda						
P. brevipes	0.9	0	0.04	6.02	0	0
Total	93.3%	--	552.17	12.46	0.10	56.29
All organisms+	100.0%	--	567.29	37.95	0.24	58.40

HUNTERS POINT Disposal Site

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nemertea	1.1%	0.91	1.28	1.65	1.08	1.49
Nematoda	1.4	0.25	3.49	2.75	0.71	1.77
Oligochaeta	1.5	0.27	1.96	4.84	0.97	1.43
Polychaeta						
E. lourei	19.2	27.26	24.17	18.80	6.73	26.25
M. californiensis	9.8	5.42	7.72	22.75	9.29	14.03
Arthropoda						
A. milleri	54.9	21.24	283.17	1.44	1.24	15.17
L. dubia	2.0	0.99	[illegible]	2.16	0.24	0.94
C. acherusicum	1.5	0 -	0.32	0.03	0	9.44
Total	91.4%	56.34	329.77	54.42	20.26	70.52
All organisms+	100.0	60.40	336.99	66.84	28.32	90.31

Adjacent to Dredged Channel

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nematoda	1.1%	0.17	7.71	0.75	5.95	[illegible]
Oligochaeta	95.9	5.74	480.06	446.70	379.09	371.50
Polychaeta						
S. benedicti	1.9	0.12	8.95	15.64	3.85	4.21
Total	98.9%	6.03	496.72	463.09	388.89	[illegible]
All organisms+	100.0	8.71	500.73	468.35	393.20	382.40

Adjacent to Disposal Site

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nematoda	4.7%	0.04	3.83	0.10	5.03	3.05
Oligochaeta	73.3	0.04	113.37	6.40	44.62	23.15
Polychaeta						
S. benedicti	10.0	0.16	21.82	1.00	2.21	0.22
T. parvus	4.7	0	12.01	0	0	0
Mollusca						
M. arenaria	2.8	0.04	2.80	1.97	1.60	0.68
M. balthica	1.1	0	0.16	0.07	1.51	1.15
Total	96.6%	0.28	153.99	9.54	54.97	28.25
All organisms+	100.0%	0.70	156.53	11.53	57.53	29.18

OAKLAND INNER HARBOR

		Survey P (3/73)	1 (9/73)	2 (12/73)	3 (3/74)	4 (6/74)
Nematoda	4.7%	8.27	20.35	54.10	89.56	52.03
Oligochaeta	31.8	132.05	277.17	491.73	525.46	69.80
Polychaeta						
S. benedicti	45.2	289.59	372.18	855.26	567.23	18.92
E. lourei	3.3	53.27	14.63	44.26	18.76	10.62
P. paucibranchiata	0.9	1.73	11.09	31.53	0.24	
Mollusca						
G. gemma	8.4	56.78	85.78	118.35	116.99	[illegible]
Total	94.3%	540.99	781.20	1,595.23	1,318.24	158.04
All organisms+	100.0	571.70	849.08	1,677.59	1,377.95	171.11

*Numerical percentage of all noncolonial organisms collected.
+All noncolonial organisms collected.

TABLE 6 (CONTINUED)

Percentage of Population*

REDWOOD CITY HARBOR Dredged Channel

		Survey P (3/73)	Survey 1 (9/73)	Survey 2 (12/73)	Survey 3 (3/74)	Survey 4 (6/74)
Nematoda	5.3%	1.12	22.45	14.13	20.57	42.37
Oligochaeta	26.2	1.50	74.21	66.24	42.03	316.70
Polychaeta						
E. lourei	7.3	3.40	52.70	18.01	29.40	33.01
S. benedicti	4.1	0	0.91	0.09	10.43	68.56
Polycirrus sp.	3.4	0	63.00	0.12	0.03	0.10
P. ligni	1.6	0	7.82	14.13	5.83	2.82
Sphaerosyllis sp.	1.4	0.04	3.15	4.46	11.50	8.24
Arthropoda						
A. milleri	39.7	6.52	350.09	183.30	65.83	133.49
Acarina	2.7	0	0	5.66	18.97	27.47
S. zostericola	1.4	0	5.03	5.60	7.63	8.46
Mollusca						
M. senhousia	1.2	7.96	4.27	4.27	0.93	0.32
Total	94.3%	20.54	583.63	316.11	213.15	641.54
All organisms+	100.0	27.40	596.09	324.59	230.70	702.37

Adjacent to Dredged Channel

		Survey P (3/73)	Survey 1 (9/73)	Survey 2 12/73)	Survey 3 (3/74)	Survey 4 (6/74)
Protozoa						
Foraminifera	1.9	0	0	1.38	3.14	16.83
Nematoda	6.4	2.13	1.46	8.21	6.47	51.26
Oligochaeta	15.8	5.64	4.02	21.96	45.80	94.53
Polychaeta						
S. Benedicti	25.3	0.06	21.59	89.78	126.41	41.49
E. lourei	3.4	6.65	1.28	9.21	1.86	14.21
C. pygodactylata	1.7	0.45	1.43	6.42	7.34	2.46
H. filiformis	1.6	6.24	1.93	1.16	1.19	2.62
Sphaerosyllis sp.	1.2	0.11	0	2.61	0.13	10.94
Arthropoda						
A. milleri	32.3	1.21	37.23	70.88	71.83	175.99
S. zostericola	2.3	0	0.44	8.49	1.68	11.65
Copepoda	2.1	0.04	0	1.73	0.06	21.91
Mollusca						
M. senhousia	1.5	6.73	0.78	0.91	0.90	1.97
Total	95.5%	29.26	70.16	222.76	269.81	445.86
All organisms+	100.0	36.73	72.80	227.55	273.27	471.91

SOUTH BAY Disposal Site

		Survey P (3/73)	Survey 1 (9/73)	Survey 2 (12/73)	Survey 3 (3/74)	Survey 4 (6/74)
Nematoda	8.7%	6.25	0.65	63.27	14.50	3.33
Oligochaeta	21.4	3.00	10.62	129.52	37.12	37.16
Polychaeta						
E. lourei	13.4	5.18	41.34	29.42	50.48	8.13
H. filiformis	2.7	3.61	1.73	5.26	7.60	7.38
Sphaerosyllis sp.	2.2	0.02	2.02	4.62	15.73	0.63
P. caulleryi	1.8	0.45	11.82	1.15	3.62	0.66
S. benedicti	1.4	0.09	4.02	2.69	1.00	5.75
Arthropoda						
A. milleri	23.2	3.50	194.38	1.92	1.78	22.24
Acarina	6.7	0	0	1.38	68.64	0.49
S. zostericola	1.6	0	6.61	4.74	3.69	1.24
C. acherusicum	1.5	0.30	0.42	0.13	0.26	13.07
Copepoda	1.3	0	0.12	0.77	12.39	0.34
Mollusca						
T. japonica	6.0	2.57	4.61	25.35	4.82	21.95
M. senhousia	3.1	4.54	0.24	0.03	25.24	0.60
Total	95.0%	29.51	278.58	270.25	246.87	122.97
All organisms+	100.0	33.77	288.10	283.94	255.66	135.66

Adjacent to Dredged Channel

		Survey P (3/73)	Survey 1 (9/73)	Survey 2 12/73)	Survey 3 (3/74)	Survey 4 (6/74)
Nematoda	3.9%	5.48	0	28.63	0.09	1.09
Oligochaeta	13.0	8.87	1.92	63.24	28.09	20.61
Polychaeta						
E. lourei	13.8	21.04	6.61	64.26	12.38	19.55
S. benedicti	7.6	0.06	2.09	23.30	3.12	46.48
H. filiformis	3.4	0.77	3.63	14.82	8.67	5.18
P. ligni	1.8		0	6.13	7.35	4.27
C. cirratus	1.4	0	0.24	10.74	1.36	1.24
Sphaerosyllis sp.	1.4	0.69	0	8.15	1.27	2.97
Arthropoda						
A. milleri	33.4	4.85	157.02	10.27	2.25	148.70
Acarina	5.7	0	0	55.24	0	0.24
C. acherusicum	3.2	3.04	0.12	0.06	0	26.88
S. zostericola	1.0	0	0.27	3.60	2.07	4.21
Mollusca						
M. senhousia	1.1	1.90	0.35	6.10	0.43	0.73
T. Japonica	0.9	0.12	2.77	3.30	1.82	1.18
Total	92.5%	46.82	181.79	297.34	69.46	285.21
All organisms+	100.0	53.17	187.26	326.46	75.80	306.79

*Numerical percentage of all noncolonial organisms collected.
+All noncolonial organisms collected.

In general, the species present a diverse, estuarine fauna. Extending beyond Central Bay, north into San Pablo and Suisun Bays and south into South Bay, the numbers of species dwindle. Widely fluctuating temperatures and salinities at the lower end of South Bay and the predominance of freshwater in Suisun Bay are probably the major limits to the diversity of animals in these regions. In Suisun Bay, the bottom fauna is primarily of freshwater origin although some marine species inhabit the lower reach of Suisun Bay. Most of the species found in the San Francisco Bay system belong to genera that are found in most temperate estuaries of the world.

In contrast to the rest of the Bay system, Suisun Bay is a brackish to freshwater environment. A "faunal break" separates the brackish and freshwater biota from the salt water biota. The faunal break occurs in a transition zone where most estuarine organisms cannot cross and successfully survive on the "other side" and vice versa with organisms of freshwater origin. For an estuarine system where freshwater grades into salt water, the transition zone is primarily dictated by salinity. This zone moves upstream or downstream depending on freshwater flow. In San Francisco Bay, with normal freshwater flows, the zone is in the vicinity of eastern Carquinez Strait. In general, the fauna west of this zone (San Pablo Bay southward) is quite homogeneous, with the great majority of organisms of estuarine origin. The fauna east of this zone (Suisun Bay and upstream) is derived mainly from the freshwater aquatic habitats of central California (exceptions are introduced exotic species that have successfully survived).

Compared to the other three sub-bays, the Suisun Bay subtidal bottom supports relatively few bottom animal species. Of the three major groups (Annelida, Arthropoda and Mollusca), the annelids and arthropods are the most numerous. Particularly abundant are the polychaetes, *Neanthes succinea* and *Polydora uncata* (*Neanthes* being an important food item for young-of-the-year striped bass), and the amphipod *Corophium spinicorne* (which is also heavily preyed upon by young striped bass).

Crustacean and bottom fish species are principal animals in the epibenthic habitat. A well known crustacean is the juvenile Dungeness crab (*Cancer magister*). In San Pablo, Central and South Bays, there are at least 13 species of bottom fish. These generally include gobies, sculpins, flounders (flat-fishes), sharks and rays which are important predators of the three major groups of subtidal invertebrates in the Bay. Worms, clams and amphipods form the main diet of these bottom fishes. Flounders, particularly starry flounders, are abundant in the Bay and are a popular sportfish. Several species of sharks, such as the leopard shark, brown smoothhound and the spiny dogfish, are also caught by anglers but are not prized as sportfishes. The more numerous bottom

fishes of Suisun Bay are the white catfish, Sacramento sucker, carp and the staghorn sculpin (western end of Suisun Bay). The white catfish preys on the amphipod Corophium, annelid worms and clams, and the staghorn sculpin in Suisun Bay feeds on worms and shrimps. The white catfish (Ictalurus catus), which is the most abundant catfish species in California, is a very popular sportfish especially in the Delta. Approximately one-third of the catfish caught in California are from the Delta, of which most are the white catfish species.

(6) Open Bay. The open bay habitat is divided into two broad communities, the plankton and nekton communities with the plankton community characterized by floating or weak swimming plants and animals, and the nekton community characterized by free-swimming fish and marine mammals.

Plankton constitute many kinds of plants and animals that either live their entire lives in the water column or live a brief portion of their lives (usually the young stages) in the water column and spend the remainder of their life cycle on the bottom. Phytoplankton is the plant component and forms the first link of the food web which eventually incorporates all other life forms in the Bay. Phytoplankton plays the same role as saltmarsh plants and the benthic diatoms of the tidal flats by converting inorganic material into nutrient-rich organic foods that can be assimilated by its predators. As a by-product of synthesizing organic material, the phytoplankton also produces large amounts of oxygen and thus helps keep the water well oxygenated. The phytoplankton community principally includes diatoms, green algae and dinoflagellates.

Seasonality of phytoplankton abundance is quite pronounced in the Bay. From San Pablo Bay south, the population peaks in spring and is at a minimum in fall, whereas in Suisun Bay, the population, essentially all freshwater species, climaxes in late summer and is lowest in the winter. Suisun Bay contains fewer species of phytoplankton than the other three sub-bays but has a ten times greater population. Maximum concentrations in Suisun Bay are estimated to be about two million cells per liter. The minimum concentration in Suisun Bay is about equal to the maximum concentration in the lower reach of South Bay. Not all species of phytoplankton in the same area climax at the same time, however. For example, in Central Bay, the overall maximum abundance occurs in spring but green algae and certain species of diatoms are more frequent during the summer and dinoflagellates in the winter.

Zooplankton is the animal component. Unlike phytoplankton, the zooplankton cannot synthesize food from inorganic material and thus must prey on those that do the synthesizing or upon other zooplankters to obtain the necessary nutrients.

Seasonal abundance of zooplankters is not as easily discernible as that of phytoplankton, but in general, zooplankters are most abundant in the summer and least in the winter and early spring in Suisun, San Pablo and South Bays. In Central Bay, seasonal changes are much more complex. In north Central Bay, the zooplankton peaks in summer with an apparent secondary peak in the winter. For the rest of Central Bay, there are also two peaks during the year, one in spring and the other during summer. The complex seasonal pattern of zooplankton in Central Bay is due to the greater diversity of species in this sub-bay than in the other sub-bays, and each species or group of species has its own cyclic pattern.

The most common zooplankter group by far are the copepods. Both the adult and nauplii (larval) stages are abundant and occur throughout the Bay system but are most common in Central Bay. Other important types of animals that make up the zooplankton community are: cirripedes (young, free-swimming stages of barnacles), polychaete larvae, gastropod veligers (swimming stage of snails) and numerous fish eggs.

There are approximately ninety species of pelagic fish inhabiting the Bay system, ranging from strictly marine to strictly freshwater species. Probably one of the most abundant fish in terms of numbers and biomass is the northern anchovy, Engraulis mordax. This species is an ocean fish that moves into bays to spawn in late spring and early summer. Large schools of adult anchovies enter the Bay during the spawning period and leave by late summer. Their eggs are free-floating and are part of the zooplankton community. Along with the rest of the zooplankton, enormous quantities are preyed upon. Immature anchovies are found from South Bay to San Pablo Bay year-round (to a lesser extent in Suisun Bay), and since they are plankton feeders, they feed on the abundant Bay plankton. Adult anchovies are an important commercial harvest of the ocean and are used primarily for bait.

A species similar in feeding habit and commercial importance is the Pacific herring, Clupea harengus. The herring migrates in large schools through the Golden Gate during winter and early spring and spawns in the shallows of Angel, Alcatraz and Treasure Islands, tidal flats of Marin coast from the Golden Gate to Richardson Bay, and along the shorefront of Richmond from Point San Pablo to Point Richmond (and sometimes into Carquinez Strait).

Other fishes similar in shape and feeding habit (plankton feeders) to the anchovy and herring that are of some importance to the commercial or sport fishery are the smelts (surfsmelt and whitebait smelt), and silversides (jacksmelt and topsmelt). Smelts are of minor importance to the sportfishery whereas the silversides are popular sport fishes in the Bay. Both silverside species spawn in the Bay. The jacksmelt is found in deeper waters of the Bay, in contrast to the topsmelt which is frequently found over tidal flats.

Of all the organisms in the Bay, the anadromous fishes are the most important commercially and recreationally. Anadromous fish spawn in freshwater and live the rest of their lives in the ocean and/or the estuary. The fish in this group include twelve species, listed in Table 7.

TABLE 7

ANADROMOUS FISHES OF SAN FRANCISCO BAY

Common Name	Scientific Name
Pacific lamprey	Lampetra tridentata
Western river lamprey	Lampetra ayresii
Green sturgeon	Acipenser medirostris
White sturgeon	Acipenser transmontanus
American shad	Alosa sapidissima
Steelhead rainbow trout	Salmo gairdnerii
Coho (Silver) salmon	Oncorhynchus kisutch (rare)
Chinook (King) salmon	Oncorhynchus tshawyscha
Pink salmon	Oncorhynchus gorbuscha (rare)
Chum salmon	Oncorhynchus keta (rare)
Sockeye (Red) salmon	Oncorhynchus nerka (rare)
Striped bass	Morone saxatilis

Economically speaking, the chinook salmon and the striped bass are the two most important members of this group. The annual commercial catch of chinook salmon is worth more than two million dollars while the striped bass is the principal sport fish in an industry worth over seven and one half million dollars.

Probably the most important spawning area for chinook salmon (Oncorhynchus tshawyscha) along the California coast is the Sacramento-San Joaquin River system. According to California Fish and Game, approximately 75 percent of California's entire annual chinook salmon landings (commercial and sport fisheries) emanate from the Sacramento-San Joaquin River system. Annual commercial landings approximated 500,000 fish within the last few years and sportfishing catch of chinooks in the ocean has exceeded 100,000 fish. In the Sacramento River, another 25,000 chinooks are annually taken by anglers.

There are evidently three distinct genetic groups of chinook salmon that spawn in the Sacramento-San Joaquin River system as identified by three separate spawning runs per year. These are known as the fall, winter and spring runs. The fall run is the largest of the three

and the natural reproduction of this run is supplemented by three hatcheries in the Sacramento River tributaries. Several hundred thousand chinooks constitute the fall run. Spawning occurs from October to March after which the adult chinooks die. The young move downstream to the ocean from January through July.

The salmon is indigenous to this coast, but the striped bass (Morone saxatilis) was introduced from the Atlantic in the 1870's. Obviously stripers have adapted well to their new environment since they are one of California's top ranking sportfish. For the most part, the striped bass is confined to the Bay estuary although some venture outside the Golden Gate. Some are caught from Tomales Bay south to Monterey Bay.

During the summer and winter months, the majority of the striped bass population (which is estimated to be between 1.5 and 4 million) is found in San Pablo Bay southward. The spawning migration begins in the spring and moves upstream through the Delta into the Sacramento River. Few stripers migrate into the San Joaquin River above the Delta. The major spawning areas are in the Delta between Antioch and Venice Island and in the Sacramento River, where spawning takes during April and May in the Delta, and during May and June in the Sacramento.

MAN'S INFLUENCE

Many past activities by man have altered the Bay system so much that it is a managed system rather than a natural system. Major activities include:

- Hydraulic mining of gold in the Sierras contributing large sediment loads to filling the Bay,
- Regulation of water flows in the Delta with storage reservoirs, irrigation withdrawals and diversions to Southern California,
- Diking the marshes in the Delta for agricultural purposes,
- Diking and filling the periphery of the Bay,
- Groundwater withdrawal causing subsidence,
- Discharge of municipal and industrial waste,

- Introduction, both intentional and non-intentional, of various species such as striped bass and certain ship fouling organisms to the system,

- Development of waterborne commerce.

No judgment is presented here as to the beneficial or adverse consequences of the above and other activities. The activities, however, are part of the description of the Bay in terms of the unknown factors in evaluating the impact of any one activity.

DREDGING ACTIVITIES

Dredging operations in San Francisco Bay move about 7.6 million cubic meters of sediment annually. The Corps of Engineers dredges about sixty percent of the total with maintenance of twenty Federally authorized navigation projects. These projects, together with the frequency, average annual cubic meters and traditional disposal site, are listed in Table 8 and shown on Figure 8. The remaining quantity of dredged sediments is moved by the various port authorities, private industry with waterfront facilities such as oil transfer facilities, and public and private marina operators.

Three types of dredges are employed in San Francisco Bay: the trailing suction hopper dredge, the clamshell dredge and the hydraulic cutterhead dredge. The hopper dredge is the predominant type used for maintenance of Federal channels. Clamshell dredges are used primarily for maintaining depths around wharves and piers. Hydraulic cutterhead dredges are used in small marinas and shallow draft channels where land areas are available for confined disposal.

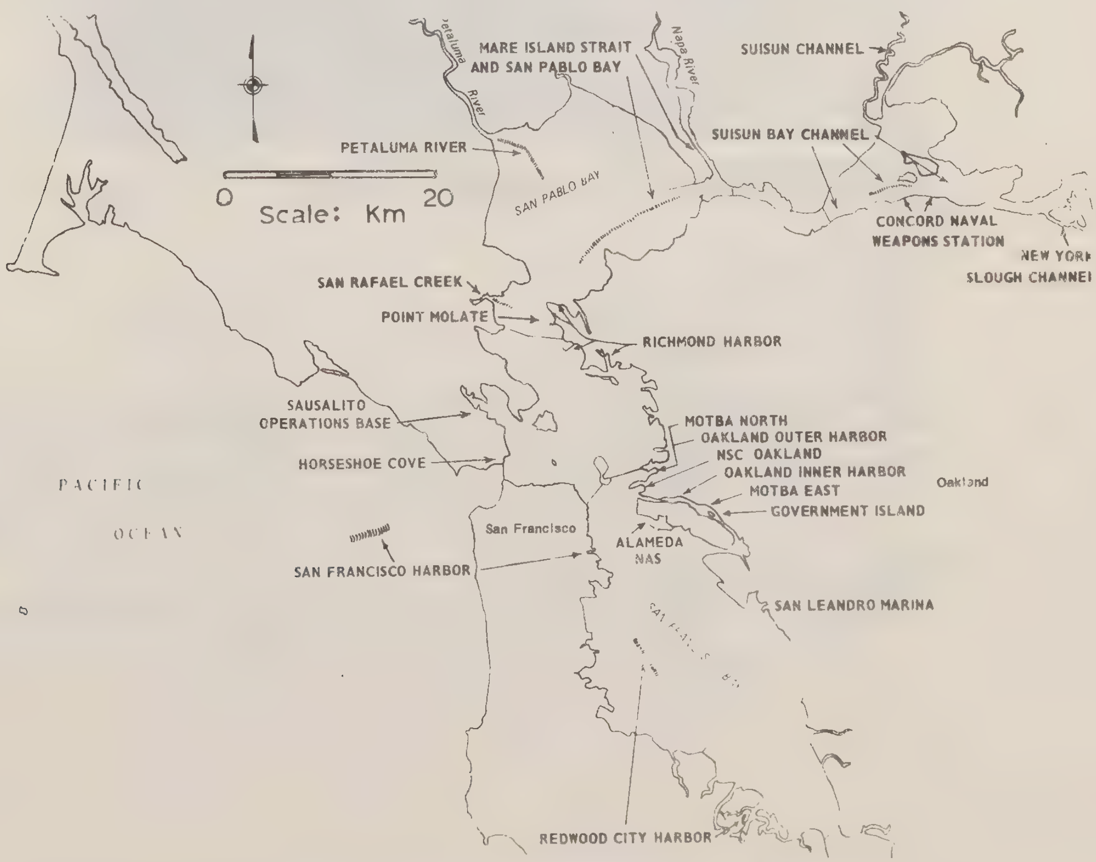


FIGURE 8 DREDGING AREAS

TABLE 8

CORPS MAINTENANCE DREDGING PROJECTS

Location	Frequency (Years)	Disposal Site	Annual Average Quantity ($10^3 M^3$)
Suisun Bay			
Suisun Bay Channel	1	Suisun Bay	170
Suisun (Slough) Channel	2-3	Land	55
New York Slough	3-5	Land	3
San Pablo Bay			
Mare Island Strait &	0.5	Carquinez Straits	1,910
San Pablo Bay Channel	2	San Pablo Bay	250
San Rafael Creek	6-8	Alcatraz and Land	26
Petaluma River	12	Land and San Pablo Bay	25
Central Bay			
Richmond Harbor	1	Alcatraz	370
Point Molate (Navy)	2-3	Alcatraz	70
MOTBA East (Navy)	3	Alcatraz	30
Sausalito Operations Base	3-4	Alcatraz	20
MOTBA North (Military)	Indefinite	Alcatraz	8
Horseshoe Cove (Army)	Indefinite	Alcatraz	1
South Bay			
Oakland Harbor			
Oakland Outer Harbor	1	Alcatraz	230
Oakland Inner Harbor	1	Alcatraz	270
Redwood City Harbor	1	Land	250
Alameda NAS (Navy)	1	Alcatraz	690
NSC - Oakland (Navy	2-3	Alcatraz	38
San Leandro Marina	5-6	Land	32
Gov. Island (Coast Guard)	5-10	Alcatraz	1
Ocean			
San Francisco Main Ship Channel	1	San Francisco Bar	760

The trailing suction dredge is a sea-going vessel designed to hydraulically lift the sediment from the bottom with drag arms pulled through the sediment and collect the sediment in hoppers. The vessel is used for both the dredging and the transport of the sediments. In the Bay, hopper dredge disposal is restricted to open water sites with sediments released through gates on the bottom of the vessel. Two dredges are used in San Francisco Bay: the BIDDLE (single 2,300 cubic meter hopper) and the HARDING (two hoppers with combined capacity of 2,000 cubic meters). Most of the field studies of dredging and disposal operations investigated the effects of these dredges. The HARDING is shown in Figure 9. Neither of the two dredges has direct pumpout capability which would enable placement of the dredged material in confined disposal areas.

FIGURE 9 HOPPER DREDGE CHESTER HARDING

The clamshell dredge is an anchored platform with a swinging boom and clamshell and is used strictly for the dredging phase. It lifts sediments mechanically as opposed to hydraulically. Horizontal movement of the dredge is achieved by swinging on spuds using anchor lines. A supporting system of tugs and barges provide the collection and transport facility. Field studies were conducted on the dredge BOSTON using a fourteen cubic meter bucket. The BOSTON is shown in Figure 10. The barges used for in-barge measurement studies and for the 100-fathom release monitoring have capacities of about 1,530 cubic meters.

FIGURE 10 CLAMSHELL DREDGE BOSTON

The hydraulic cutterhead dredge is an anchored platform with pumps. The sediments are broken mechanically with the cutterhead and lifted hydraulically through a suction pipe. The sediments are transported in a slurry via a pipeline to a land disposal site. Horizontal movement of the dredge is achieved with spuds and anchor lines. Limited field monitoring was performed with the Navy's 0.46-meter hydraulic cutterhead dredge at Mare Island shown in Figure 11.

FIGURE 11 NAVY HYDRAULIC CUTTERHEAD DREDGE

The majority of sediments dredged in San Francisco Bay are released at open water disposal sites. Figure 12 shows the general location of the sites. The majority of disposal occurs at either the Carquinez Strait or the Alcatraz Island sites. The site on the San Francisco Bar is used exclusively for disposal of sand from the Main Ship Channel across the Bar. In 1972, regulation of disposal by the Corps and the Regional Water Quality Control Board reduced the number of open water sites within the Bay from eleven to five. Due to the poor flushing characteristics of South Bay two sites in South Bay were eliminated. An additional open water site was added in Suisun Bay. An experimental site was established in Central Bay on a one time basis to monitor availability of contaminants (Appendix I). In addition, an ocean site is located along the 100-fathom (183-meters) line outside the Golden Gate.

FIGURE 12 OPEN WATER DISPOSAL SITES

SEDIMENT RESUSPENSION AND INTERACTION WITH WATER

INTRODUCTION

Dredging and disposal activities inherently cause a disturbance and redistribution of bottom sediments. A major element necessary for evaluating the environmental impact of a dredging or disposal operation is the determination of the interactions between sediment and water during this disturbance and redistribution. The characteristics of this interaction dictate the nature of potential physical and/or chemical effects which may be adverse to the biological system. Field and laboratory studies were undertaken to quantify the degree and duration of sediment-water interactions at selected dredging and disposal locations in San Francisco Bay.

The type of sediment (i.e., sand versus silt or clay) and the water content of the sediment are the primary controlling parameters used in determining the degree of sediment-water mixing and interaction (Appendices C and M). These parameters also influence the duration of the interaction, that is, the time required for particles to settle out of the water column and the time necessary for transport of sediment away from the open water disposal sites. Without flocculation, a large portion of the sediments (fine silts and clays) would remain suspended for long periods in the water column.

Several methods are used for measuring sediment resuspension. The most typical representation is in terms of turbidity which is quantified as percent light transmission or light reflectance. Weight and volume of sediment are other parameters which can be used to measure the content. Each measurement has its own application in defining impacts. Optical measurements are especially useful for studies related to photosynthesis and productivity. Suspended solids measurements are used to determine such impacts as clogging of gills, physical interference with functions and chemical mobilization of contaminants.

INTERACTION DURING DREDGING

During the dredging process several different operations (i.e., cutting, lifting, etc.) occur which result in disturbance and resuspension of bottom sediment. Factors which are important during the dredging operation in addition to type of sediment are the size and type of

equipment and the site conditions. These vary in how they impart energy to the system and how they contribute to the adding and mixing of water. Figure 13 indicates areas of sediment resuspension during dredging. Table 9 summarizes the operations of each of the three types contributing to sediment disturbance.

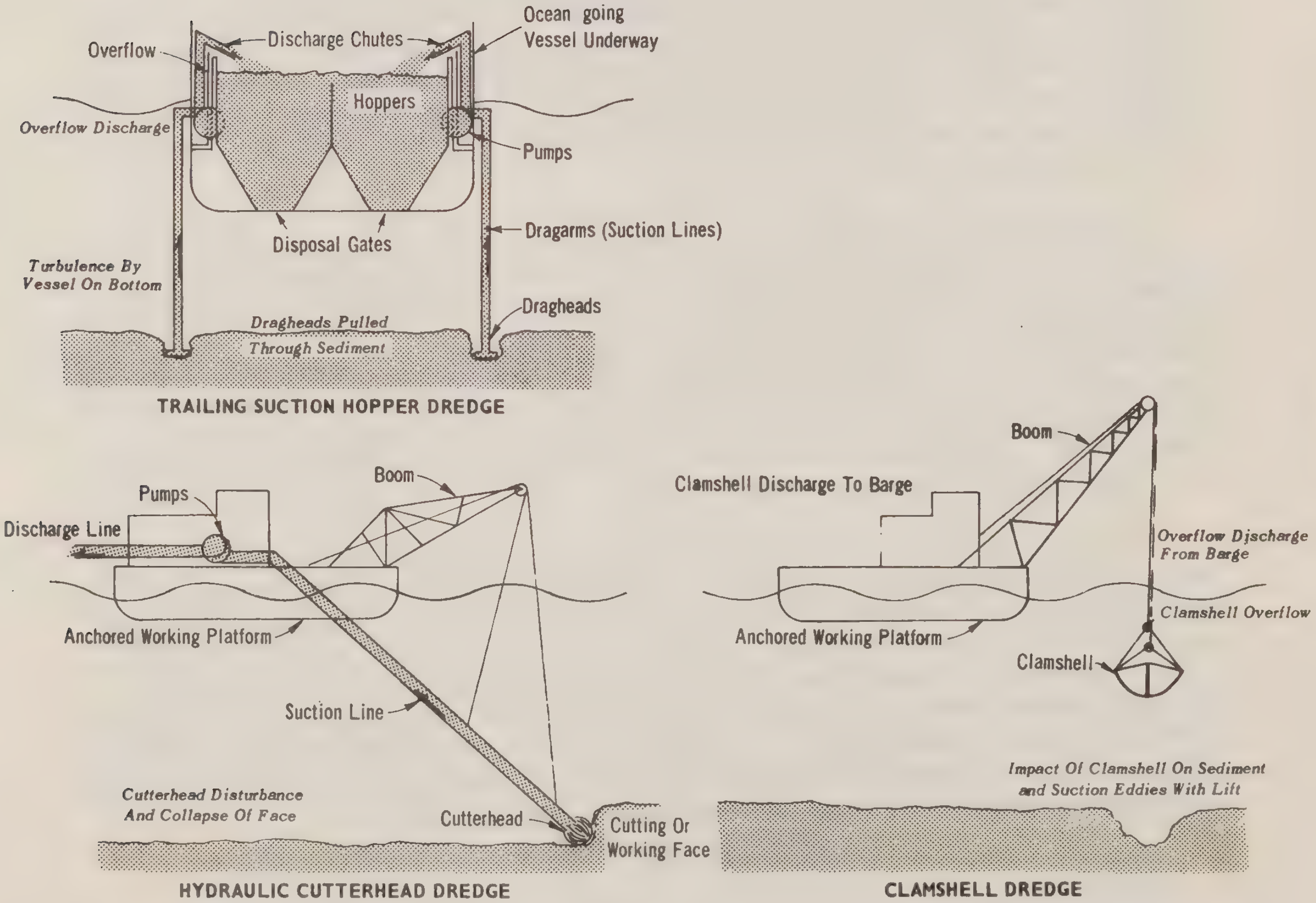


FIGURE 13 AREAS OF SEDIMENT RESUSPENSION DURING DREDGING

TABLE 9

OPERATIONS CAUSING SEDIMENT RESUSPENSION
DURING DREDGING

Vessel Type	Movement	Time of Operation	Cutting	Lifting Thru Water	Loading
Trailing Suction Hopper Dredge	Yes	Intermittent (About 1 hr. cycle)	Yes	No	Yes
Clamshell Dredge	No	Continuous	Yes	Yes	Yes
Hydraulic Cutter-head Dredge	No	Continuous	Yes	No	No

The trailing suction hopper dredge, because of its size and means of propulsion, is the only one of the three dredges that disturbs the bottom material as a result of vessel passage and prop-wash. However, this phenomenon is not unique to a hopper dredge but occurs whenever a vessel with a relatively deep draft uses a channel (5). All three dredges cause agitation of the sediments during the cutting operation. The hopper dredge disturbs the bottom sediments when its two trailing drags pass through the shoal. The clamshell dredge disturbs and resuspends bottom sediment as the "bucket" bites into the sediment and breaks free upon being hoisted. The hydraulic cutterhead dredge is continually resuspending sediments as long as the cutter is crowding or advancing into the sediment face. Not all of the sediments being suspended by the hydraulic cutterhead are drawn into the suction pipe; varying amounts can be carried away by currents, especiallv following collapse of the working face. The pipelines of the cutterhead and hopper dredges reduce disturbances in the water column as the sediments are moved from the Bay floor to the surface. In contrast, the bucket of the clamshell dredge loses sediments as it is raised through the water column. These sediments continue to be lost during the loading operation as the bucket breaks free of the water surface and is swung to the dump scow or barge. Water charged with particulates can re-enter the water column when water is intentionally displaced from the scow or when inadvertent spillage occurs. Similarly, the hopper dredge discharges a water-particulate mixture during the overflow periods. At the start of filling the hopper or barge, water occupies the volume of the vessel below the water surface. This is because the bottom gates, through which the sediments are released, are not water tight. These overflow periods in the loading of both the hopper and the barge are intended to displace this water in the vessels with solids to obtain the highest practical solids density (called economic load as opposed to maximum load).

*Site conditions also influence the degree of disturbance and thus the nature and duration of the sediment-water interaction. Site conditions of importance include the sediment characteristics previously discussed, depth or face of the cut, spacing and shape of the dredging areas and restrictions. Restrictions placed on the type of dredging equipment which may be used in certain areas, although not a common factor, can significantly influence the degree and/or the duration of disturbance. The type of equipment which can be used for the channel dredging over the Alameda Tubes in Oakland Inner Harbor, for example, has been limited to the hopper dredge to insure that dredging operations do not damage the tunnels. The length and shape of the cut required over the tubes decreases the operating efficiency of the drag arms of the hopper dredge, thereby increasing the amount of water pumped and, in turn, increasing the overflow from the hoppers. This and the other parameters influence the efficiency of the dredging operation and therefore influence the degree and duration of sediment disturbance and interaction.

Studies were conducted in 1974 - early 1975 in Mare Island Straits, Richmond Harbor and Alameda Naval Air Station to quantify the dredging plume in terms of suspended solids and percent transmission. Table 10 presents representative results for each project area. The effect of salinity on flocculation is indirectly apparent when concentrations of plumes are compared between areas. The concentrations are higher in Mare Island Strait, where salinity is lower than it is in the Central Bay projects. Figure 14 depicts an estimated maximum plume configuration for Mare Island Strait channel associated with hopper dredge use. The velocity of the dredge relative to the bottom is maintained at two knots (one meter per second). In general, the plume extends from the dredge both in the upper water column, due to overflow, and the lower water column. As distance increases from the dredge, the upper plume merges with the lower plume to attenuate light transmission and distribute solids throughout the water column. Solids concentrations in the upper and mid water column rarely exceed several hundred milligrams per liter except directly adjacent to the hopper dredge overflow ports. Concentrations in the bottom waters are a gram per liter or more. At approximately 300 to 400 meters downstream of the hopper dredge a clear zone appears in the mid to lower water column probably due to particulate agitation and aggregation caused by the variable pitch, twin screws of the vessel. The plume can extend more than 700 meters downstream. Typically as distance from the dredge increases the extent of the plume becomes increasingly more limited to the bottom waters. However, as evident from the results in Richmond Harbor, surface discoloration can also extend nearly this far downstream. The suspended solids concentrations decrease with distance from the dredge whether hopper or clamshell. Samples were taken adjacent to discharge ports to determine the maximum loading in the upper water column during periods of hopper dredge overflow. Concentrations as high as 8.7 grams per liter were measured. These concentrations are reduced quickly to the hundred

milligram per liter range. This is reflected in the data presented in Table 10. The suspended solids concentrations 50 meters downstream from the clamshell dredge were similar to the hopper dredge concentrations in the upper and mid water column. However, they were several times lower in the lower water column. The plume was about 300 meters long on the surface and about 450 meters long near the bottom.

TABLE 10

TYPICAL SEDIMENT DISTURBANCE IN WATER COLUMN DURING DREDGING

			DISTURBANCE ALONG LINES PARALLEL TO DREDGE											
			Centerline				50 m. off Centerline				100 m. off Centerline			
	BACKGROUND		% Trans.		mg/l		% Trans.		mg/l		% Trans.		mg/l	
PROJECT	% Trans.	mg/l	Length	Level	Max	Ave	Length	Level	Max	Ave	Length	Level	Max	Ave
(Hopper Dredge)														
Mare Island Strait														
1 m. Depth	25	33	275	0	210	210	140	0	60	43	140	35	12	12
5 m. Depth	15	83	600	2	110	64	180	14	46	46	230	9	49	49
10 m. Depth	1	123	750+	0	1,110	743	750+	0	2,600	337	750+	1	260	233
Richmond Harbor														
1 m. Depth	75	31	680	0	82	65	275	25	51	45	685	35	23	23
5 m. Depth	65	33	700	0	39	33	180	55	55	55	140	57	20	20
10 m. Depth	60	39	275	2	200	145	180	55	-	-	90	63	32	32
Alameda Naval Air Station														
1 m. Depth	75	35	275	0	188	131	-	-	-	-	-	-	-	-
5 m. Depth	72	28	600	-	47	42	0	-	-	-	-	-	-	-
10 m. Depth	70	38	700	40	58	58	-	-	-	-	-	-	-	-
(Clamshell Dredge)														
Alameda Naval Air Station														
1 m. Depth	50	24	275	10	170	70	275	30	40	29	-	-	-	-
5 m. Depth	56	34	450	5	172	88	400	0	214	68	0	-	33	29
10 m. Depth	69	37	450	8	118	33	-	-	-	-	-	-	-	-

Note: All Channels 10.5 m. deep except Alameda Naval Air Station clamshell area which is 9 m. deep.
% Trans. = Percent light penetration thru 10 centimeter light path.
Length = Distance in meters with reduced light penetration.
Level = Lowest percent light transmission reading not necessarily sustained over the length.

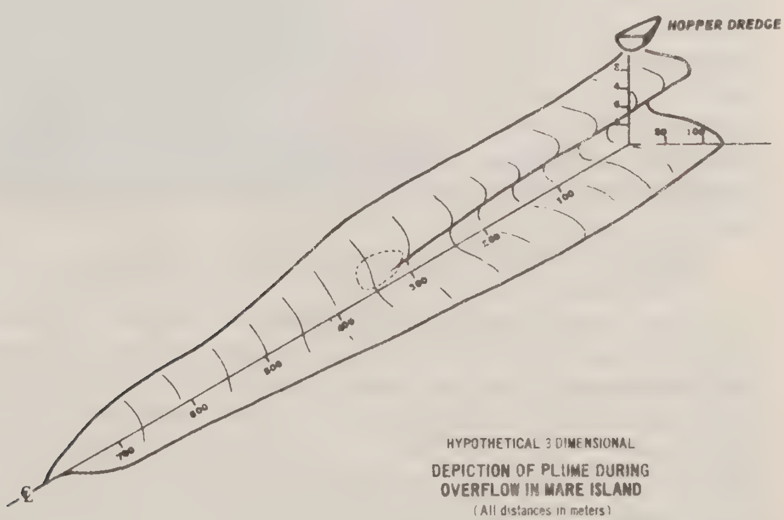


FIGURE 14 HOPPER DREDGE PLUME

Instances have been observed in Mare Island Strait when the mixing of the bottom salt water with surface fresh water by dredging actually reduced the suspended solids loading in the upper water column.

At the sediment-water interface, the dredging operation can cause a fluff similar to that occurring during storm conditions or periods of high sediment transport into the Bay. The phenomenon occurs because of the "hindered settling" of the sediments at concentrations greater than about ten grams per liter. The particles flocculate and aggregate, causing arching of particles and trapping of water. The "hindered settling" increases the time required for consolidation of the bottom sediments. The condition is generated by the physical disturbance to the bottom sediments followed by settling of the resuspended sediment. Water samples in the lower water column have contained two grams per liter suspended solids. The sediments in shoals requiring maintenance dredging are 450 to 500 grams per liter of solids with water contents of about 85% by volume. Limited information has been obtained because many areas of the Bay naturally lack a well defined bottom or "fluff" is not always generated. Circulation of tidal flows with filling through bottom water and emptying via surface waters as occurs in many of the dredging projects (e.g., Mare Island Strait, Oakland Harbor, Richmond Harbor and Alameda Naval Air Station) cause the lack of a well defined bottom or fluff to remain in the dredging site.

INTERACTION DURING DISPOSAL

After the sediments are loaded either in a hopper or in a barge, they are transported to one of the designated disposal sites in the Bay or off the coast. During the dredging operation, the sediments are disturbed (the strength properties of the sediments are reduced or eliminated) due to the physical action of handling the sediments with the bucket or through the pumps and the addition and mixing of water. The addition of water occurs during the cutting operation and during the loading as the excavated sediment mixes with the residual water in the hopper or barge. The physical properties of the sediment are not significantly altered during transport to the disposal site by either the duration of the haul or vibration during the haul (Appendix M).

The physical properties of the sediments, intensity of disturbance and the resulting change in water content affect the release pattern of the sediments into the open water system. During open water disposal the sediments are released through the bottom of the disposing vessel, about seven meters below the water surface for hopper dredges and about five meters for barges. Surface discoloration appears adjacent to the hopper dredge when the pumps start just prior to the release (pumping adds water to the hoppers resulting in overflow) and when the suspended solids remaining after the sediments pass through the water column are

agitated by the twin screws of the vessel. The suspended solid concentrations of the most turbid water on the surface during disposal were found to be as high as 733 milligrams per liter. With Bay mud, the water content of the sediment and the degree of disturbance to the sediment during dredging are the controlling factors in determining the dispersion pattern of the sediment as it passes through the water column.

Two releases of Bay mud from new construction dredging with a clamshell were monitored at the 100-fathom (183 meters) test site (Appendix L). The test site had a sandy substrate with phosphatic nodules as shown in Figures 15 and 16. The sediments passed through the water column and mounded in clumps as shown in Figure 17.

FIGURE 15 OCEAN BOTTOM AT 100-FATHOM TEST SITE

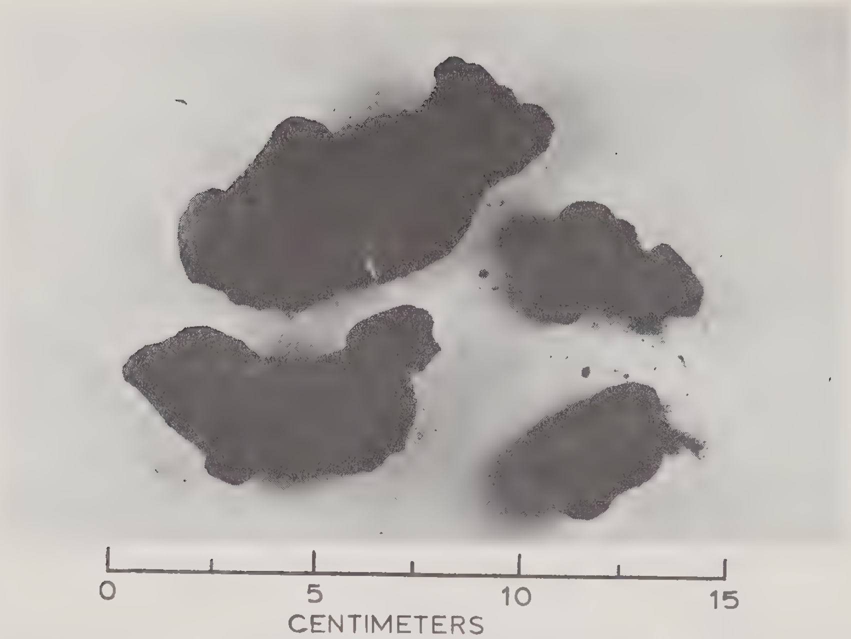


FIGURE 16 NODULES AT 100-FATHOM TEST SITE

FIGURE 17 CLUMPS RESULTING FROM 100-FATHOM TEST SITE RELEASE

Releases from a hopper dredge monitored at the Carquinez Strait Disposal Site resulted in plumes on the bottom with a horizontal transport velocity independent of the tidal currents. The results of the disposal study at Carquinez Straits (one release displayed in Figure 18) with concentrations 0.25, 0.5 and 1.5 meters off the bottom revealed several important findings. First, the solids concentration can be two orders of magnitude higher (20g/l) in a well-defined plume within two meters of the bottom than in the remaining water column (0.2g/l). Second, the plume did not always pass a specific point (station) as a homogeneous mass. Instead, in many cases, two pulses in different stages of coincidence occurred. Additionally, the plume did not have a uniform concentration gradient with time. The concentration of suspended solids generally seemed to build rapidly followed by a much slower decrease. Third, the highest solids concentration was consistently found at the station positioned on the lower slope of the disposal site. Fourth, cloud velocity initially seemed to be independent of current velocity. Total suspended sediment concentration in the water column above the top of the cloud (estimated to be no more than two meters off the bottom) was about one to five percent of the total sediments in a hopper or barge load, depending on the dredging conditions and the disposal site.

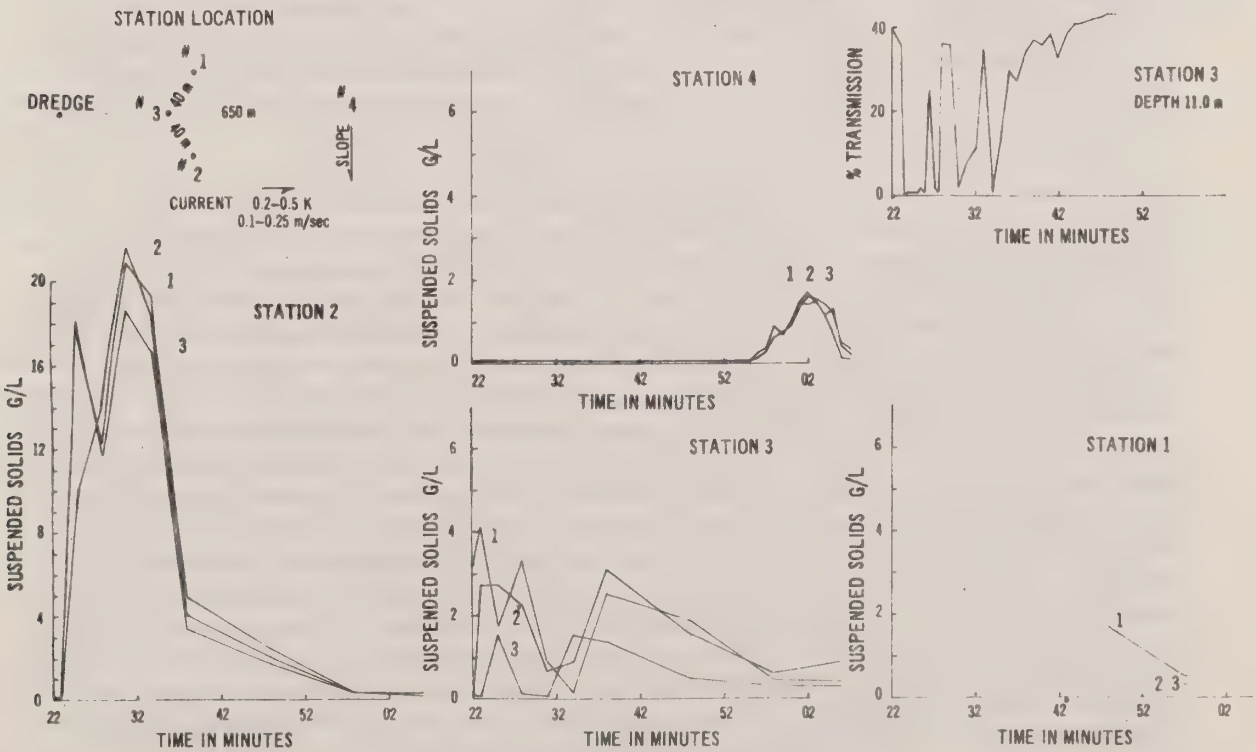


FIGURE 18 SEDIMENT TRANSPORT - CARQUINEZ STRAIT DISPOSAL SITE

The dredged sediment released at a disposal site possesses an initial downward momentum and a density greater than that of the surrounding water (7). These two factors result in forces that cause the material to settle in the form of a cloud, or density current, rather than settle as individual particles. This is called the convective descent phase and occurs very rapidly (6). Settling velocities calculated for individual particles do not apply during this form of transport. The time during which the cloud is in contact with the upper portions of the water column is in the order of a minute or less. Thus, ambient water currents, except near the bottom, are of little consequence in dredged sediment placement (7). Currents are important as they affect the transport of the turbidity cloud that may be generated during the descent. Such a cloud is formed by overflow just prior to release and by disturbance due to the prop wash, the vessel passing through the site, and by the shear stresses developed at the interface between the descending material and the ambient water. These stresses result in dissipation of the initial momentum and in the creation of turbulent eddies that entrain water and result in spinoffs from the main cloud. The sediment in the upper water column represents a very small percentage of the total mass (1 to 5 percent).

The second phase of transport occurs when the cloud begins a dynamic vertical collapse, characterized by horizontal spreading upon contact with the bottom (6). Collapse is driven primarily by pressure forces, and resisted by inertial and frictional forces. The material flattens out and is similar to the base surge cloud in underground detonations as it assumes a horizontal circular shape with small vertical dimensions.

Since the hopper dredge HARDING has two hoppers, the twin injection results in two plume fronts which affect each other. The plumes act as fluid muds with mean concentrations of about 10 grams per liter. Each plume interface moves progressively out of the disposal area as a density flow. Gravity, inertia and the density gradient provide the dominant driving forces. In addition, the slope of the bottom at the Carquinez Strait is steep enough to maintain the fluid flow. Initially, currents have very little effect on transport. They are overshadowed by the effect of the density gradient between the surrounding water and the sediment mass, and the sloping bottom. The effect of the slope causes the two divergent wave fronts to be altered from a predicted concentric pattern to a skewed pattern down slope and a compressed pattern up slope. The merging wave fronts between the two hoppers collide and generate a new or secondary wave front which moves off perpendicularly to the axis of collision illustrated in Figure 19. The perpendicular movement is caused by the generation of a new vector following the interaction of colliding plume wave front vectors. The primary and secondary wave fronts can interact with each other in three ways.

First, a single, unamplified peak (wave front) which does not reflect any enhancement from another wave front is generated by each hopper. Second, two peaks indicating two wave fronts can be observed which are the two primary waves from the two hoppers. They augment each other and thus increase the total suspended solids concentration at an instantaneous place and time. Third, a single amplified peak can be observed when the two wave fronts are in phase. The mean duration of increased solids concentrations at any single point is approximately 17 minutes. The concentration curve at any single point generally follows a skewed (right) shaped distribution during this time period, such that there is a rapid initial increase in solids, followed by a much longer period of solids decrease.

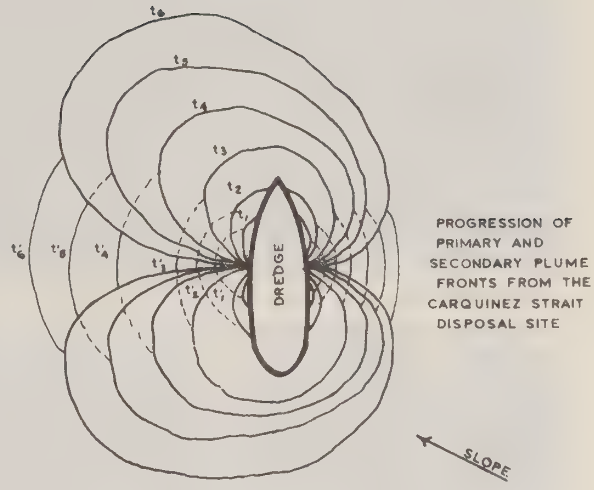


FIGURE 19 INTERACTION OF TWO PLUMES

Initially, the velocity of the wave front is less than the current velocity. As the wave front progresses outward, the solids content decreases because of water entrainment and deposition. At the same time that the density of the flow is decreasing, its velocity is increasing.

As the plume moves out from the release point, the cloud is essentially confined to the lower two meters of water column. Above the bottom surge cloud, the water mass is negligibly affected and suspended solids concentrations remain near ambient levels. Minor fluctuations do occur as the wave front passes above this two meter height but solids concentrations are an order of magnitude lower. The percent transmission measurements on Figure 18 illustrate this point. These measurements were taken at depths of 11 to 12 meters, which was three to four meters off the bottom. The instrument being used will not show a reading when the suspended solids concentration is greater than 200-300 milligrams per liter. This instrument recorded zero transmission only twice during the survey period. As long as the probe was positioned more than two meters off the bottom, solids concentrations never approached the magnitude of the concentrations found in the cloud. Previous measurements during other studies at this disposal site have shown negligible turbidity in the upper and mid water column.

Finally, as distance from the release point increases, the vertical concentration gradient becomes more nearly homogeneous. Analyses of the three sampling depths (0.25, 0.5 and 1.5 meters off the bottom) show that the solids concentration at the two lowest depths were typically greater at the 1.5 meter depth.

The release of sandy sediments (those which do not have cohesive properties) results in a reaction entirely different from sediments with cohesive properties such as Bay mud. The sandy sediments react as discrete particles, depositing in a predictable pattern. Studies conducted on the San Francisco Bar showed a normally-distributed pattern with a maximum deposition of two inches directly beneath the hopper dredge (Appendix A). The deposition approached zero at about 120 meters perpendicular to the centerline of the dredge. The disposal site on the San Francisco Bar, as well as the presently used open water disposal sites within San Francisco Bay, are high energy areas, causing the released sediments to be quickly assimilated into the natural sediment regime.

During the disposal of dredged sediments, three patterns have been observed in the field during the study - mounding of Bay mud, dispersion of Bay mud and mounding of fine sand. Laboratory studies were conducted to determine the controlling factors (Appendix M). Figures 20 and 21 show two simulated releases in a 1.2 meter deep tank. The controlling parameters were found to be the type of sediment and the degree of disturbance to the sediment in terms of increased water content. The disturbance can be in terms of water added, mixing of sediment and water and, with a clamshell operation, size of the bite. The figures show results using silt with a low water content (Figure 20), and clay with a high water content (Figure 21). In both cases, very little disturbance occurs in the upper water column. The disturbance in the lower water column is significantly less with the lower water content. Although both releases cause a bottom plume, the low water content sediment is essentially intact on the bottom (clump on bottom left with a low density plume) as compared to the high water content sediment which disperses over the bottom (high density plume). Several things worth noting include the potential of released sediments to entrain water during descent, the lower horizontal (or spread) velocity of the higher density plume and the greater independence of the higher density plume from the boundary conditions of the tank. The hydrodynamic phenomenon is driven principally by inertia effects with the reaction to the inertia (type of cloud formed) determined by the cohesive properties of the sediment. A cohesive sediment with little disturbance (introduction and mixing with water) will descend through the water and mound on the bottom with little, if any, disturbance to the water column. If the cohesive properties are less because of added water or higher silt content, the slurry will entrain water during the descent, form a base surge cloud on the bottom, and disperse over a large area. As the sediment moves through the water column, water entrainment occurs, increasing the water content and resulting in a greater dispersion of the sediments. Currents and wind-wave conditions at the disposal site

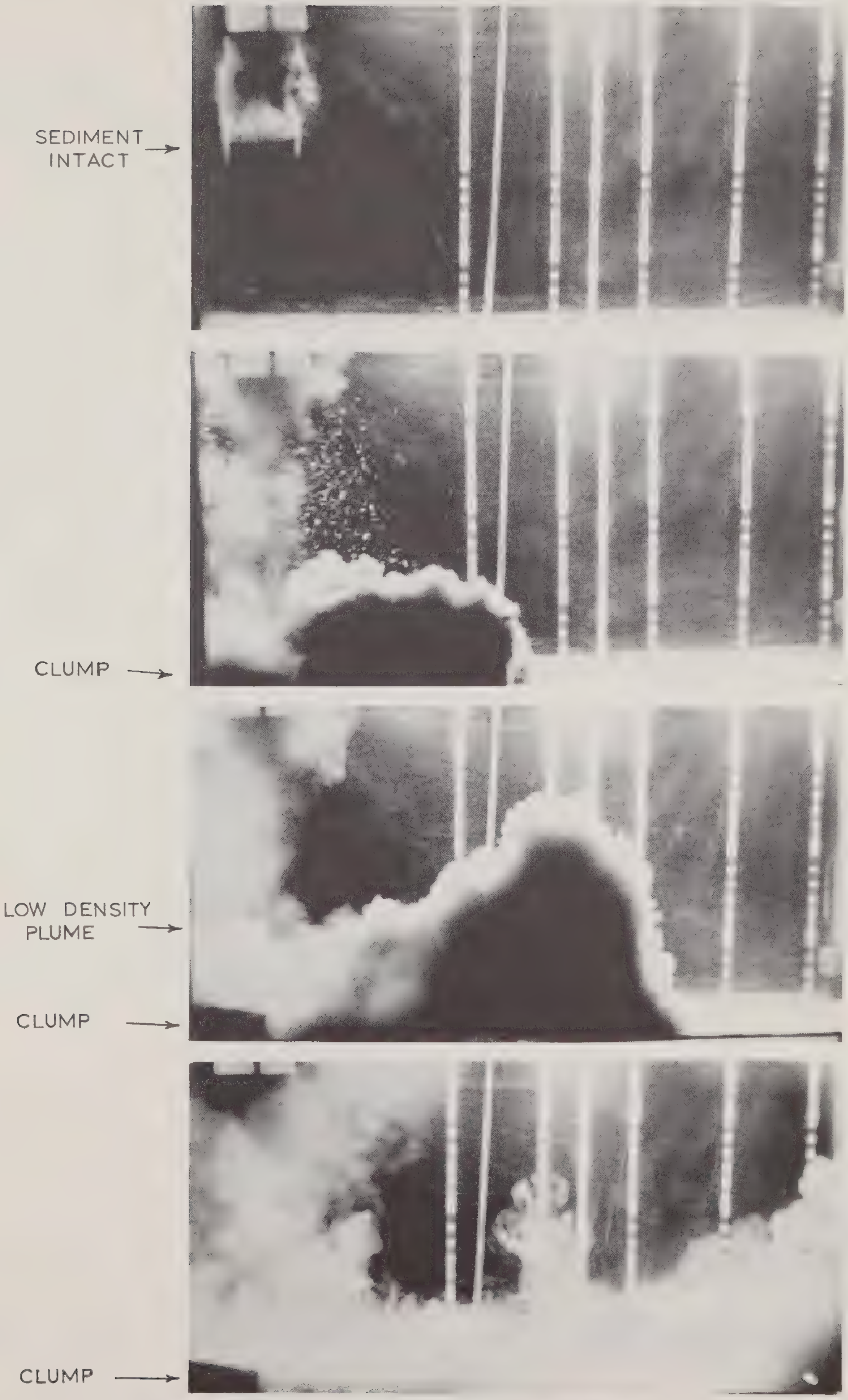


FIGURE 20 LABORATORY RELEASE - SILT WITH LOW WATER CONTENT

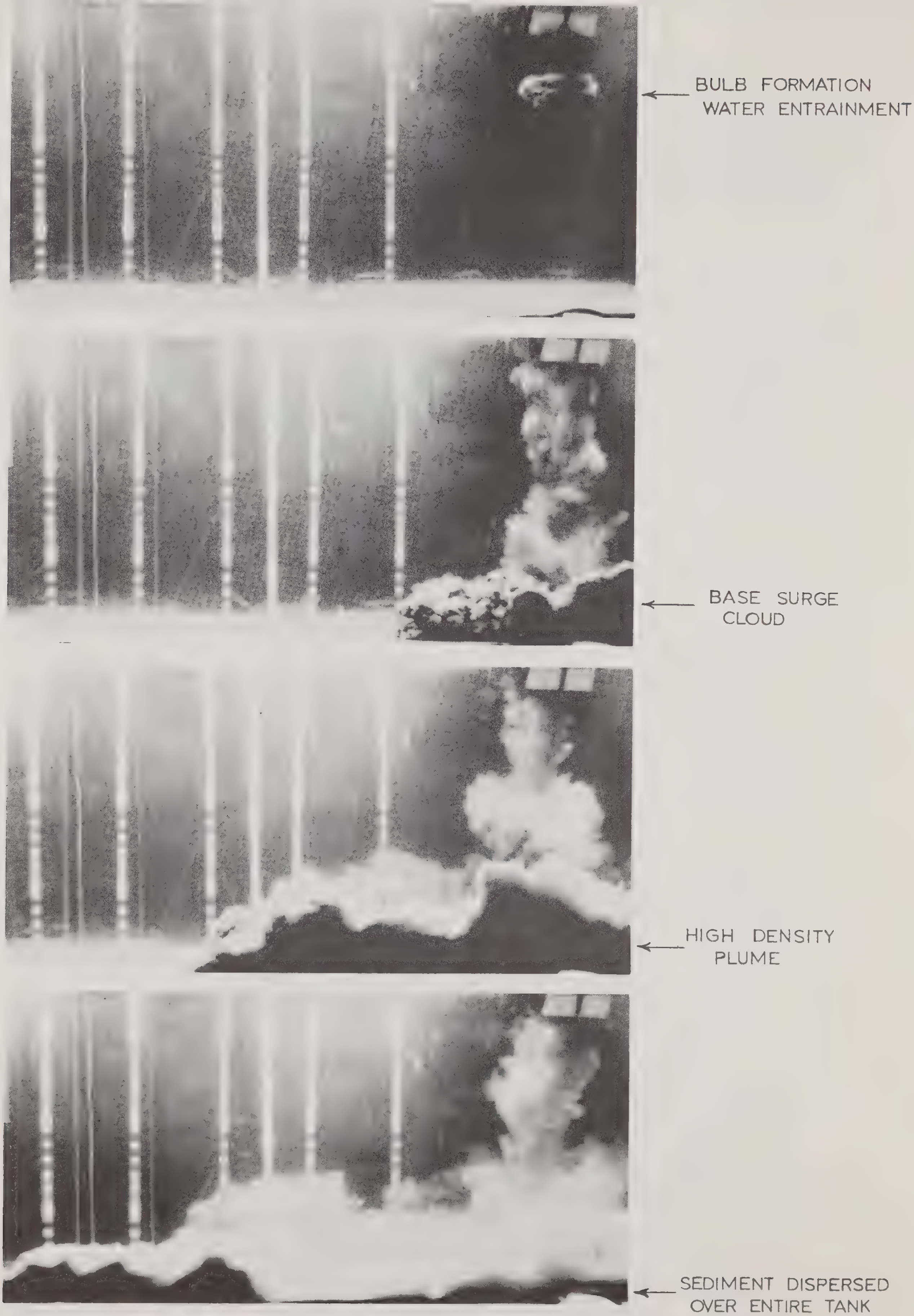


FIGURE 21 LABORATORY RELEASE - CLAY WITH HIGH WATER CONTENT

do not, initially at least, influence the movement of the density flow as long as its momentum is greater than that of the surrounding water. The currents and bottom slope will influence the skewness of the base cloud. Ultimately, as the density of the cloud decreases, the currents will control the long-term dispersion and transport of the sediment.

To predict or evaluate the physical conditions generated at the disposal site during a release, information on the engineering properties of the sediment and type of dredging operation is required. The primary engineering properties are the grain size distribution and the liquid limit. With cohesive sediments, the release pattern (degree of initial dispersion or mounding) can be correlated with the liquid limit and the moisture content of the sediment. The degree of initial dispersion or mounding depends on whether the sediments act as a solid, a liquid or a transitional slurry. Cohesive sediments require a disturbance in terms of water added; whereas, sands, regardless of water content, act as a solid phase. This theorization is depicted in Figure 22. The water content to define the transition zone with cohesive sediments are about two and four times the liquid limit of the sediments for the lower and upper ranges, respectively.

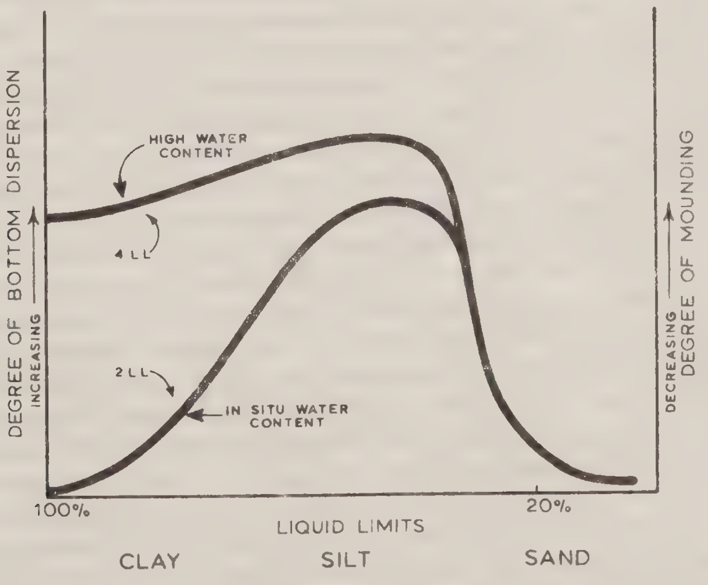


FIGURE 22 SEDIMENT RELEASE PATTERN

FATE OF RELEASED SEDIMENT

An estuary such as San Francisco Bay is both a sink and a holding area for fluvial sediment in transit to the ocean from soil erosion in the Bay's extensive drainage system. Sediment entering the Bay system is either temporarily or permanently held in residence, depending on the dynamic conditions in the estuary. Surficial bottom sediments quickly respond to changes in the distributing forces from wind-wave action and currents. The nature and energy of the forces responsible for development of a profile of equilibrium fluctuate from moment to moment. However, there are seasonal patterns manifested by these forces (e.g., river inflow, wind characteristics, wave climate, tidal action, and sediment availability) that will result in seasonal trends of deposition and erosion.

Inflowing sediment is not, for the most part, carried directly to the ocean. A large percentage of the inflowing sediment remains in residence in the Bay for a number of years, being deposited, then resuspended, recirculated, and redeposited elsewhere, with the net effect of being transported toward the mouth of the estuary and out of the Bay system into the ocean as suspended load and bedload. Most new sediment enters the Bay system during the months of maximum runoff (winter). When the sediment-laden freshwater mixes with the saltwater, aggregation and settling occur. The broad expanses of the shallow bays, where tidal velocities are low, are the repository areas for the aggregated sediments. During the winter months wave suspension of sediment is at a minimum, allowing accumulation of sediments. In the spring and summer months, daily onshore breezes generate waves over the shallow areas, resuspending sediments and maintaining them in suspension, while tidal and wind-generated currents circulate them throughout the Bay. The suspended sediments are repeatedly deposited and resuspended in the shallow areas until they are finally deposited in deeper water below the effective depth of wave influence. In spring and summer there is a net movement of sediment from the shallow repository areas, bringing the shallows back to a profile of equilibrium where wave action is no longer influential in resuspending the sediment. Once the sediment reaches deeper water, usually in natural channels or along the margins of these channels, tidal currents become the primary transporting mechanism. Like the shallow areas in equilibrium with the depth of effective wave action, the depth of the natural channels is in equilibrium with the flow volume and current velocity in the channel. When resuspended sediments from the shallows are transported into the natural channels, the sediment has a tendency to be transported along the channel in the direction of net flow. Sediments may be transported by tidal currents back into shallow areas, especially after the sediment has been transported through a constricted strait into a broad bay, such as through San Pablo Strait into Central Bay, or moved back into the fresh-saltwater mixing zone in Carquinez Strait with net water movement upstream near the bottom and mixed upward with flows moving into the Bay.

Some sediment is permanently retained in the Bay system. This sediment is deposited and accumulated in low energy areas where wind-wave action and waterflow volumes and velocities are not great enough to transport sediments. These areas may be found along the margins of the Bay such as intertidal flats, marshes and inlets, as well as around manmade structures and dredged channels. Marshes trap sediments by decreasing flow velocities and wind-wave action to the extent that a portion of the sediments may no longer be flushed out. Inlets and sloughs provide sheltered areas with very low current velocities.

Dredged navigation channels are out of equilibrium with the system in that the channels are maintained to a depth greater than the natural depth. Maintenance of dredged channels is required since the channels, with few exceptions, will tend to regain the equilibrium depth of their surroundings. Flow velocities in these dredged channels are usually not great enough to maintain required depths. For this reason, sediment that accumulates in maintained channels will remain there until the channels are dredged.

Shoaled sediment may be derived directly from sediment inflow to the Bay or it may be derived from some part of the resuspension-recirculation-redeposition cycle. Shoaling rates in the dredged channels are not constant but vary from year to year, depending on the variable sediment inflow volume, wind-wave action and current velocities. During a season of exceptionally high sediment inflow into the Bay, for example, dredged channels will normally experience higher sedimentation rates than usual, both in winter and spring-summer seasons. The same process occurs in the shallow areas where the depths of accumulation will be greater, thus reducing water depths. In the spring-summer season shoaling in the dredged channels is due to redistribution of sediment accumulated in the shallow areas during the winter.

Disposal of dredged sediments in the Bay brings back into circulation material that would otherwise remain out of circulation (retained in the channel). Upon disposal, the dredged sediment will reenter the deposition-resuspension-redeposition cycle, eventually being permanently placed in low energy areas or carried to the ocean. Since dredged channels are out of equilibrium, some of the disposed dredged sediment will likely reenter the same or other dredged channels.

Sites for disposal of dredged sediment in San Francisco Bay are in natural channels or along their margins. No net accumulation of dredged sediments in any of the disposal sites has been detected since disposal operations at the sites were initiated. Disposal of dredged sediment in these high current velocity areas and the present practice of using the closest disposal site towards the ocean from the dredging site has the effect of eliminating one or more steps of the resuspension-recirculation-redeposition cycle and accelerating the process of transporting sediments through the estuary to the ocean.

The major transporting mechanism of the dredged sediments in the natural channels is by tidal currents and occurs at depths greater than the depth of effective wave action. Just as the water has a tendency to remain in the natural channels, as evidenced by the high current velocities, dredged sediments also have a tendency to remain within the confines of the natural channels for at least a short period of time.

The natural channel network in the Bay leading to the ocean is not continuous, causing the dredged sediments, like the natural sediments, to leave the boundaries of the natural channels and move onto the shallows as part of the resuspension-recirculation-redeposition cycle. The dredged sediments moving onto the shallows are dispersed and do not inhibit the system's ability to resuspend and recirculate the material. In contrast, if "low wave energy-low current energy" disposal sites were used for deposition of dredged sediments in the Bay, the ability of the system to assimilate the dredged sediments or the ability of the dredged sediments to reenter the resuspension-recirculation cycle could be significantly reduced. For example, disposing in north San Pablo Bay shallows during the winter, when wind-wave resuspension is at a minimum, could, conceivably, cause a large enough accumulation of dredged sediments that wind-wave resuspension in the subsequent spring-summer season would be insufficient to remove all the material. The result of such an action would decrease the water depths in the surrounding area, further decreasing the wave action and the ability to resuspend and circulate the sediment. This would disrupt the existing equilibrium, resulting in a net accumulation of sediments in the shallows.

Based on tagging studies (Appendix E) the dispersion of dredged sediments after disposal at the Carquinez disposal site was found to be very rapid. During the dredging operation, however, dredged sediments make up a large percent of the total sediment in and around the disposal site. In March 1974, while dredging of Mare Island Strait was still continuing, large quantities of dredged sediments were found in the sampled 80 square kilometer area around the disposal site, including dredged sediments that had re-entered the dredged channel. After the completion of dredging operations at Mare Island Strait dredged sediments were found dispersed in April 1974 over a 260 square kilometer area including San Pablo Bay, Carquinez Strait and Suisun Bay. Localized areas were found in San Pablo Bay that had higher percentages of dredged sediments. By August 1974, five months after dredging had been completed, very little evidence of dredged sediments was present in the first 23 centimeters of sediment over the 260 square kilometer study area.

In September-October 1974, large quantities of dredged sediments were found in the upper 23 centimeters of sediment. The increase was due to the redredging of sediments in Mare Island Strait and the wind-wave recirculation of sediments on the shallows of San Pablo Bay. A large portion of the dredged sediments in October was located in the natural channel leading to San Pablo Strait and Central Bay. By December

1974, most of the dredged sediments were again absent from the study area. The volume of dredged sediments dredged in February-March 1974 was 1.2 million cubic meters. Table 11 gives the distribution of the sediment over the 260 square kilometer area in terms of the portion of the upper 23 centimeters of sediment which originated from the disposal operation. The distribution is the percent of study area with a range of dredged sediment concentration.

TABLE 11

PERCENT OF STUDY AREA WITH
VARIOUS PERCENTAGES OF DREDGED SEDIMENTS

	0-0.5%	0.5-2%	2-4%	4-8%	8-40%
April 1974	18	29	19	25	9
August 1974	86	14	0	0	0
October 1974	51	19	8	10	12
December 1974	71	20	6	3	0

Generally, the dredged sediments were well distributed between the three sample layers making up the 23 centimeters. In many areas the vertical distribution was greater than 23 centimeters, showing either a greater vertical mixing or a deposition of other sediments.

Analysis of samples obtained from Mare Island Strait and the hopper during dredging and previous studies of the area indicated that about 10 percent of the dredged sediments returned to the dredged channel.

CHEMICAL REACTIONS

During sediment/water interaction certain chemical reactions can occur in the water column as a result of the intrinsic chemical nature of the disturbed sediment and the existing environment. Probably the most common chemical reaction occurring during sediment resuspension is the consumption of dissolved oxygen by reduced substances in the anoxic sediment matrix. Other potentially important reactions include pH changes, desorption of chemical toxicants and/or biostimulants from organic and inorganic constituents.

Studies were conducted to evaluate chemical reactions occurring during dredging and disposal activities in San Francisco Bay and incorporated both laboratory and field examinations (Appendices C, F, H and I). Primary attention was given to the characterization of the dissolved oxygen concentration of the receiving waters as modified by operations. Other standard parameters monitored were salinity/conductivity, temperature and pH. During selected studies measurements were made of the trace element, chlorinated hydrocarbon and nitrogen releases associated with resuspension of Bay sediments.

Water quality monitoring showed that operations in San Francisco Bay do not cause a statistically significant effect on water salinity/conductivity, temperature or pH. However, both the dredging and the disposal operation influence the dissolved oxygen concentration. The effects of the dredging operation is considerably less severe than those of the disposal operation. Reductions of dissolved oxygen during dredging were detected only one quarter of the time. At the surface, overflow from a hopper dredge caused a depletion of approximately two parts per million. The oxygen concentration returned to background levels within about two minutes. Background dissolved oxygen concentrations are typically eight to nine parts per million. At the sediment-water interface reductions of as much as four parts per million were recorded. Background concentrations returned after approximately eight minutes.

The hopper dredge, because it is constantly moving, impacts discrete locations for only a short period of time; however, its effects cover a wide area. The sessile clamshell or hydraulic cutterhead dredge inversely impacts only a limited area at one time, but effects are exerted almost continuously. Dissolved oxygen reductions caused by the continual introduction of oxygen consuming materials can last the duration of the dredging project.

Disposal from a hopper dredge resulted in surface reductions of approximately two parts per million lasting for two minutes. This reduction was similar to the surface reduction caused by dredging both in terms of intensity and duration. Near the bottom, however, sediment disposal can cause a statistically significant ($P=0.05$) oxygen depletion with each release. Reductions of up to six parts per million were observed. Ambient concentrations were regained after an average of three to four minutes, but could be influenced for as long as eleven minutes. During disposal operations in San Pablo Bay, oxygen increases were detected but did not exceed one part per million.

Three factors have substantial effects on the duration and intensity of dissolved oxygen fluctuations. First, the chemical composition of the disturbed sediment influences the intensity of oxygen demand. The greater the content of oxygen consuming chemicals and organic matter and the lower the oxidation-reduction potential of the sediment, the more likely it is to pronouncedly influence the dissolved oxygen concentration during resuspension. Second, as particulate contact (surface

area) with the water column increases, the oxygen demand intensifies. Third, the amount of mechanical perturbation influences the chemical characteristics of the slurry, e.g., introducing air bubbles, and, in this way, modifying its oxygen demand and the duration of fluctuations.

The potential problem of release of harmful constituents from resuspended sediments was initially investigated in the field. Dredging activities in Mare Island Strait and disposal in Carquinez Strait were monitored to determine if the operations caused a significant change in the metal levels of influenced water (8). During the study statistically significant (P=0.05) increases in the concentrations of four (Cr, Ni, Pb, Zn) of six elements measured were observed. Mercury was found to decrease and copper levels did not fluctuate. To obtain greater understanding and quantification of the phenomena observed in the field, a laboratory study was conducted (Appendix F). The first phase characterized Bay sediments as to their physical and chemical properties. The second phase used a semi-selective extraction scheme to determine the nature of selected trace metal bonding in the sediment matrix. The third phase quantified the release of these selected metals from resuspended sediments under a variety of environmental conditions.

The results of the extraction scheme indicated that a significant portion of the investigated elements was in the residual phase. This phase is considered relatively biologically inert. Metals are strongly bound to the mineral lattice and require a strong to moderately harsh chemical attack to be released. Seventy-seven percent of the mercury, 60 percent of the iron, 54 percent of the manganese and zinc, 53 percent of the copper, 50 percent of the lead and 4 percent of the cadmium were found in the residual phase.

The constituents which are not structural components of the lattice are available for release under appropriate environmental conditions. The two factors which exert the greatest effect are the pH and the oxidation-reduction potential of the ambient environment. The pH of both the sediment and the water of the Bay are near neutrality. Any pH fluctuation is quickly buffered; thus this parameter has little effect on trace element release from Bay sediments. Of significantly greater importance is the effect of oxidation-reduction potential shifts. In the presence of sulfide under reduced conditions, many metals will precipitate forming a metal-sulfide complex. Such complexes have very low solubility. When the complex is introduced into an oxidizing environment, e.g. the water column, there is a sudden release as the heavy metal sulfide oxidizes to elemental sulfur and release of metal ions occurs. Almost immediately the released metals will precipitate or coprecipitate with available iron or manganese to form oxide or hydroxide coatings and nodules or will complex with other inorganic or organic radicals. In this form the metal complexes are again relatively insoluble.

During the selective extraction investigation various chemical treatments were used to selectively remove metal partitions. A hydrogen peroxide treatment was used to identify those metals associated with the organic and sulfide like phases. The reaction released significant amounts of metals: 92 percent of the cadmium, 45 percent of the lead, 43 percent of the copper, 39 percent of the zinc, 23 percent of the mercury, 19 percent of the iron. The chemical extractants (ammonium acetate and sodium citrate-dithionate) which should have released the metals sorbed by hydrous oxides did not appear to contain significant amounts of trace metals.

Bay sediments contain 1,000-3,000 parts per million of sulfides and thus represent a reducing environment. The association of trace metals with the sulfide phase under a reduced condition would be expected.

In the sorption-desorption experiment, five independent parameters were studied. They were oxidation-reduction potential, salinity, agitation time, solids-to-solution ratio and sediment type. The oxidation-reduction potential was found to have the greatest effect on trace metal fate. Under oxygen-rich conditions, significantly more copper, cadmium, lead and zinc were found in the elutriate solution than in elutriates under reduced conditions. Iron acted in an opposite manner with more iron found in solution under the reduced environment. One mechanism which may be the cause of these results is the release of trace metals bound to sulfide phases upon oxidation. The iron released under oxidized conditions probably precipitates as hydrous oxides which dissolve and form the more soluble Fe^{+2} species under reducing conditions.

Salinity significantly influenced cadmium and zinc concentrations in oxygen-rich samples and iron in oxygen-deficient conditions. In each case more metals were found in higher salinity elutriates than in near fresh water. Two possible mechanisms which may explain this observation are the formation of soluble inorganic complexes with the increased chlorides, carbonates and sulfates or the release of trace metals bound to ion exchangeable sites with the greater cation competition of more saline waters.

The length of agitation time significantly affected the release of cadmium, copper and zinc under oxidizing conditions. More metals were released at the longer shaking periods, suggesting that a kinetic mechanism may be playing a role in the fate of the trace metals. Possibly the oxidation of sulfide or organically bound trace metals occurs over a time interval of the order of several days to weeks to attain a steady state quilibrium.

The solids-to-solution ratio significantly affected the release of copper and iron in both oxidation-reduction states. More of these metals were found in the elutriates separated from the high solids content samples. This may reflect the effect of the larger source of trace metals in the larger sediment samples which, if desorption and/or dissolution mechanisms slightly predominate over sorption mechanisms, would be expected to show a larger release.

The release of trace metals (Cd, Cu, Pb, and Zn) under oxygen-rich conditions in general increased the water column concentration 30-200 percent. Ratios of elutriate to original water concentrations in general ranged from 1.3 to 2.0 for samples which originally had trace metal concentrations similar to values found in the Bay. The iron release was substantial under reducing conditions with ratios of elutriate to original waters ranging from 50 to 3,000. This phenomenon should be very uncommon in San Francisco Bay because the water column is not normally oxygen deficient. Under the usual oxygen-rich conditions in the Bay, iron ratios of elutriate to original water concentrations were 2 to 4. Figures 23 to 24 illustrate the levels of releases of the trace metals.

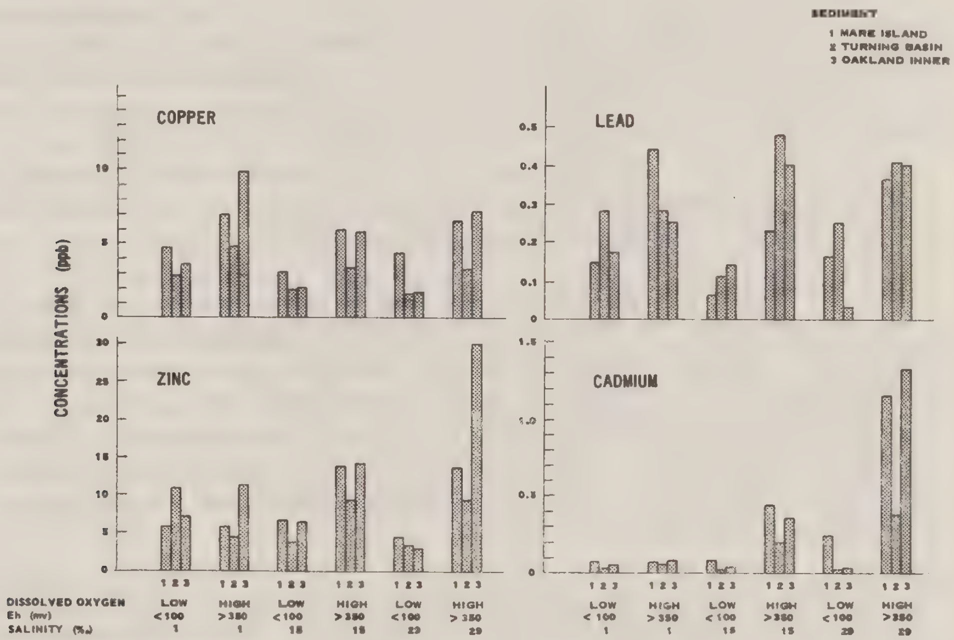


FIGURE 23 ELUTRIATE TRACE METALS' CONCENTRATIONS

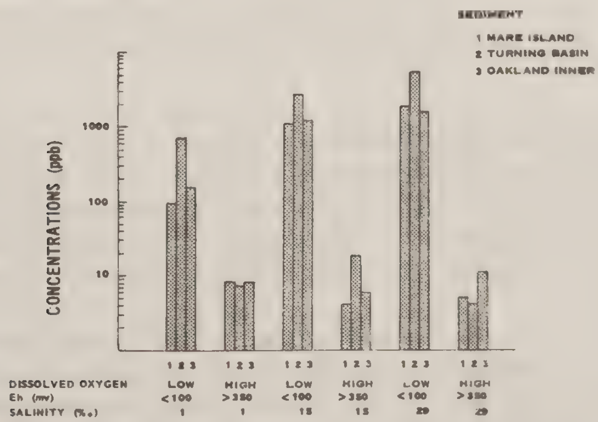


FIGURE 24 ELUTRIATE IRON CONCENTRATIONS

The initial field experiment and the laboratory investigation both indicated that under appropriate environmental conditions trace elements could be released during dredging activities. In February 1975, an experimental disposal operation was conducted to intensively study the physical, chemical and biological impact of "polluted" sediment disposal (App. I). Water sample analyses showed that solute concentration of cadmium, copper and lead increased in the disposal plume by 6, 4 and 9 times, respectively. Cadmium concentrations increased from 0.22 parts per billion (ppb) to 1.35 ppb, copper from 1.29 ppb to 5.0 ppb and lead from 0.21 ppb to 1.88 ppb. These observed increases lasted less than one and one-half hours which was the frequency of sampling.

The disposal operation was found to also increase the chlorinated hydrocarbon concentration of the water. The p,p'-DDD, p,p'-DDE and PCB Aroclor 1254 levels were observed to increase by factors of 1.6, 2.5 and 2.3 in the water and suspended particulates. Maximum observed concentrations were 0.98 ppb for p,p'-DDD, 0.44 p,p'-DDE and 6.6 ppb for PCB Aroclor 1254. The samples were collected every 30 minutes. By the second sampling following disposal, the chlorinated hydrocarbon concentrations had returned to ambient levels.

Fulk et al (9) conducted laboratory investigations to assess the extent to which chlorinated hydrocarbons may be transferred from bottom sediments to the water column. Samples were analyzed for aldrin, dieldrin, endrin, lindane, 2, 4-D esters, DDT and analogs, toxaphene and PCB as well as other constituents. Migration tests, including equilibrium and settling tests, were performed to determine the amount of pesticides and PCB associated with the solids remaining in suspension after various settling times.

They found that desorption was affected by the solids-to-liquid ratio, pesticide levels in the sediment, particle size and organic fraction, and oil and grease content. In the desorption tests, it was found that desorption occurred only at the highest ratios of sediment-to-water (1:4 to 1:5). The amount desorbed depended primarily on the concentration of pesticides in the sediment and to a smaller extent on sediment particle size and total organic carbon. Desorption was affected by the oil and grease content only at the highest sediment-to-water ratios.

During the experimental disposal operation the concentrations of nitrate nitrogen and ammonia nitrogen were monitored (Appendix I). In the plume the nitrate concentration increased from a background level of 0.3 ppm to 1.8 ppm and the ammonia nitrogen from 0.3 ppm to 3.0 ppm. These levels lasted for less than one hour, the frequency of monitoring.

Laboratory studies by others have also shown a release of nutrients (nitrogen, phosphate and silica) upon the addition of dredged sediment to the water column (10). These studies have shown a sudden release followed by a slight decrease in nutrient concentration. The highest

release of nutrients occurs under reducing conditions with agitation. Slightly oxidizing conditions result in a middle level of nutrient release while oxidizing conditions generally have releases at very low concentration levels. Silty clay sediments release comparatively more nutrients than do coarser sediment, mainly due to the finer particle size with higher concentrations of nutrients and organic matter content.

Nitrogenous compounds are known to be released upon the addition of water-sediment mixtures to the water column. The amount and form of released compounds are controlled to a large extent by the oxygen concentration of the water mass. Under oxidizing conditions, the organic nitrogen as well as the ammonium ions are oxidized to nitrate and subsequently to nitrate ions. Under anaerobic conditions the Kjeldahl (soluble) nitrogen increases in the water column. Ammonia nitrogen (10) was found to be released a maximum of ten times over ambient levels and organic nitrogen (10) a maximum of five times in the laboratory, which corresponds well with results of the field experimental disposal (Appendix I).

The occurrence of chemical reactions during the disturbance and resuspension of San Francisco Bay dredged sediments was demonstrated both in the field and in the laboratory. Reactions included the reduction of the dissolved oxygen concentration, and the release of trace elements, chlorinated hydrocarbon and nitrogen compounds. These reactions were observed to occur only in the suspended solids plume generated during operations. Dissolved oxygen levels can be reduced by more than seventy-five percent from near saturated conditions. The reduction can continue for several minutes. The release of trace constituents can measurably influence ambient concentration of these constituents in the water column. In the field, trace metal levels were found to increase by several parts per billion for durations less than one and one-half hours. Chlorinated hydrocarbons concentrations were augmented by releases in the parts per billion range for periods less than thirty minutes. Nitrate and ammonia nitrogen levels were temporarily increased by factors of 3.5 and 10 times over backgound concentrations.

These releases, although statistically significant, are considered to be low level because of the extremely small concentrations of these constituents found naturally in the water column. The duration of elevated concentrations in the water column following release was not fully quantified. However, under oxidized conditions released toxic constituents (trace elements and hydrocarbons) should reassociate with particulates almost immediately and ammonia should be oxidized to nitrate. These chemical reactions following sediment disturbance and release are augmented by the turbulent conditions at San Francisco Bay disposal sites, to reestablish pre-operation conditions in the water column.

Several reports have been published under the Dredged Material Research Program which provide information in addition to the supporting appendices. They are references 21 through 26 in the bibliography.

BIOLOGICAL IMPACT

INTRODUCTION

Dredging and disposal operations have potentials for causing biological impacts in the Bay. Impacts can result from physical and/or chemical effects. Physical impacts are readily apparent. During the excavation process organisms are removed with some mortality from the channel bottom along with the dredged sediments. Aquatic disposal can result in burial and smothering of organisms residing in the impact zone. In addition, during both these activities the water column will have elevated suspended solids concentration. Chemical reactions which might be biologically significant during operations are not as intuitively obvious as impacts due to physical disturbance. During both laboratory and field investigations statistically significant changes in water quality were observed which resulted from chemical reactions related to Bay sediment resuspension (Appendices F and I). The advent of measurable water quality changes, however, does not necessarily connote significant biological impacts.

To facilitate discussion, these two broad categories (physical and chemical) of potential impacts are discussed together under five specific areas of potential biological effect. Each area is discussed separately and assessed as to its significance to the biological populations found in San Francisco Bay dredge and disposal sites. The areas of concern are (1) bottom disturbance, (2) dissolved oxygen reductions, (3) increased suspended solids loading, (4) uptake and accumulation of toxicants and (5) biostimulation. There are other areas of potential biological concern too, such as, changes in sediment and water circulation, secondary and tertiary effects of subsequent industrialization, etc.; but this study was directed towards effects of the dredge/disposal operation and not towards other extrinsic impacts.

Because of the dispersion of the sediments, dredging of navigation channels and aquatic disposal operations have little direct influence on diked salt ponds and marshes and somewhat more on tidal flats. The fouling, benthic and open bay habitats because of their proximity to operations have the greatest potential of being impacted, and for this reason received the most emphasis during the in-Bay studies of dredging and disposal effects.

The fouling community on the pilings and wharves adjacent to navigation channels may be influenced by elevated suspended solids concentrations or other dredging-related water quality changes. The benthic community lives in close association with sediments and has substantial tolerance for particulate resuspension. However, excavation disturbs or removes these organisms in the channel area while deposition of released

sediment may smother or in other ways affect the bottom organisms at the disposal site. Open bay organisms immediately within the area of influence of either the dredging or disposal operation are subject to the same type of water quality changes as the fouling organisms. Many of them, however, are capable of escape.

Of the three habitats influenced by dredging and disposal activities, the benthic domain receives the greatest impact during the excavation and disposal process. For this reason, benthic organisms were emphasized in the biological studies performed during this investigation. However, the animals studied were not limited to members of this community. Representatives were selected from both the fouling and pelagic habitats as well, to assess effects on individual species not living in close association with the sediment.

BOTTOM DISTURBANCE

Bottom disturbance probably causes the most significant adverse biological consequences of dredging and disposal operations. Physical disruption of benthic habitats is inherent in these activities. During the excavation process typically one or more meters of surface sediments are removed from the channel. It is in these surface sediments that the majority of the indigenous benthic community resides. Although many organisms are masticated and destroyed as they are dredged, others survive to be relocated during disposal. This is particularly true when a clamshell is used and the organisms are not subjected to the violence of hydraulic pumping. Open bay species have also been found to be susceptible to entrainment and abuse during pumping operations. During subsequent disposal, the released sediment may mound to some degree. This mounding has the potential for smothering bottom species with limited abilities for vertical movement.

A census of benthic macrofauna was conducted in three dredged areas and four disposal sites in March, September and December 1973 and in March and June 1974 (Appendix D). During each of these periods, elected physical and chemical properties of the water and sediment were also measured. Four locations are of particular interest in assessing the effects of sediment disturbance at Bay dredge and disposal sites.

At Mare Island Strait, one sampling station was established in the dredged channel and another in the undredged portion of the Strait. At the Carquinez Strait disposal site, one sampling station was positioned at the center of the site and another at the northern edge. Two stations were also established at both the South Bay disposal site and Redwood City Harbor. In March 1973, immediately after the first census, a little less than 5,000 cubic meters of sediment were dredged from one

of the harbor stations and disposed at one of the South Bay disposal site monitoring stations. No further dredging activity occurred at these four stations for the remainder of the survey so that recolonization could be followed in the disturbed areas.

The survey in Mare Island Strait exemplifies the influence dredging may have on a channel's biological resources. Dredging of the Strait occurred in January, February and November of 1973 and February and March of 1974 as shown in Table 12. The samples collected in March 1974 illustrate the effect of dredging on the number of organisms in a channel area versus an undredged area. This sampling occurred during dredging. There were less than two individuals of bottom organisms per liter in the channel samples and over 390 individuals per liter in the undisturbed area. The March 1973 samples from the dredged station contained slightly greater than three individuals per liter. This sample was obtained approximately one month after dredging was completed. The September 1973 samples, obtained seven months after the termination of dredging, contained over 280 individuals per liter. The average numerical abundance at the dredged station was about eighteen percent of the abundance at the undredged station.

TABLE 12

MARE ISLAND STRAIT NUMBER OF INDIVIDUAL BENTHIC ORGANISMS COLLECTED AND PERIODS OF DREDGING

Month/Year	1/73	3/73	5/73	7/73	9/73	11/73	1/74	3/74	5/74	7/74
Dredging Dates	——					——		——		
Number of Individuals per liter										
- Dredged Station		3.3			280	20.3		1.7	11.3	
- Undredged Station		8.7			501	468		393	383	

Effects of disposal using the Carquinez Strait samples were not as easily demonstrated. This is because the area is naturally stressed by both high currents and large salinity changes and the sampling technique was not designed to enumerate abundance from patchy distributions. Patchy distributions are typical in this type of environment. The March 1974 samples during disposal showed that more than six times as many individuals per liter were at the undisturbed station as in the center of the disposal site.

Although the benthic communities surveyed in Mare Island and Carquinez Straits had the fewest species (were least diverse) of any location where the census was conducted, these communities may be among the most resilient found in the Bay. Long periods of both natural and man-induced environmental stress may have resulted in evolved resilience. Oliver et al. (11) found a positive correlation between community resilience, environmental stress and decreasing community complexity in Monterey Bay. If this relationship is true for a variety of situations, a community living in a highly stressed environment is generally less complex and can recover more quickly from a disturbance than that from a more benign environment.

The dredging and disposal experiment conducted at Redwood City Harbor and South Bay disposal site suffered from the lack of an immediate post-disturbance sampling. Rigorous characterization of recovery and recolonization thus is not possible but sampling was sufficient to permit gross trend description.

The pre-dredging census of Redwood City Harbor in March 1973 indicated that the experimental and reference stations were quite similar in species composition and relative abundance (at least for the month of March). The next sampling occurred in September, six months after the experimental dredging was completed. The number of organisms had increased about twenty times over the March sampling. Subsequent sampling into 1974 showed that this abundance progressively decreased. Although there was no reduction in total numbers of species between March and September samples at the dredged station, the species composition and numbers of organisms markedly changed. For example, 10 of the polychaete species collected in September were not present in March. Only three of the 15 arthropod species in March were common to both sampling periods (nine were new in the September samples, three that were present in March were absent in September).

Species difference between March and September 1973 at the reference station, although apparent, was not as great as at the dredged station for these two sample periods. Total population at the reference station also increased in September but only doubled as compared to a 20-fold increase at the dredged station. The doubling was primarily due to increased numbers of an amphipod, Ampelisca. A polychaete, Streblospio benedicti, and the mud mussel, Musculus senhousia, were little affected by dredging. These common species probably experienced a net reduction immediately after dredging but quickly recovered by the next sampling period (within six months) and continued to be abundant up to June 1974 when the field surveys terminated.

At the South Bay disposal site, the station which received the dredged sediment from Redwood City Harbor was situated at the southern end of the site. The reference station was established at the northern end and was presumably not influenced by the disposal at the opposite end, 1,000 meters away. Keeping in mind that there was a six-month interim between the initial sampling and the first post-disposal sampling, the survey offered no evidence of adverse effects resulting from the disposal of the dredged material. Post-disposal samples revealed little change in numbers of organisms and the dominant organisms sampled before disposal continued to dominate the benthic biota subsequent to disposal. Species composition changed little between pre- and post-disposal sampling dates except that additional species of polychaetes and arthropods were noted during the post-disposal sampling period. The increased species number was probably due to introduced species from the dredged site as well as to natural seasonal fluctuations of species in that area.

The undisturbed reference station located at the northern end of the site contained the same general dominant species as did the disturbed southern station, but the species composition was quite different between the two stations. For example, 12 taxa were found exclusively at the disturbed station whereas 22 taxa were found exclusively at the undisturbed station. However, these 34 mutually exclusive types constituted a very minor component, amounting to only 0.27 percent of the total number of noncolonial specimens collected from both stations. Later samples at the undisturbed station also revealed an overall increase in species numbers over the earlier samples, similar to that observed at the disturbed station. The changes are attributed to seasonal fluctuations.

Although not demonstrated by the experiment at the South Bay disposal site, the effects of burial on the residents of a disposal site by released dredged sediment can be significant. The impact is more severe when the deposited sediment is non-compatible, i.e. unlike the native sediment characteristic of the receiving area. Organisms seem to have exceptional difficulty exhuming themselves from alien substrates. Those organisms indigenous to a mud substrate do not have the appendages to move through a sandy overburden, and sand inhabiting organisms do not have the appendages to migrate through a mud overburden (11).

Some mortalities in the channel and disposal areas are unavoidable. These animals must be considered expendable if navigation projects are to be maintained and the present practice of aquatic disposal continued. However, if proper site selection is utilized, impact on sensitive or ecologically important species, e.g. shellfish, can be minimized.

DISSOLVED OXYGEN REDUCTIONS

A typical vertical profile of the Bay would show a column of oxygenated water overlying an 8-10 centimeter stratum of oxidized olive gray sediments and an underlying medium grey or black layer of reduced sediments. When these reduced sediments are resuspended their oxygen consumption rates increase significantly above the quiescent benthal rates.

Since resuspension significantly alters the oxygen demand rate of benthic sediments, an important consequence of dredging and disposal operations is possible reduction of the ambient oxygen at the activity. Second to perturbation of the bottom, dissolved oxygen reductions may possibly cause the most significant biological effect of dredge/disposal operations. During periods of reduced oxygen, organisms have decreased tolerance to both suspended particles and toxicants. Furthermore as stated in the 1972 Water Quality Criteria "Blue Book", "... any reduction of dissolved oxygen can reduce the efficiency of oxygen uptake by aquatic organisms and hence reduce their ability to meet demands of their environment."

In San Francisco Bay, during both dredging and disposal operations, short term (about two minutes) reductions of one or two parts per million (ppm) were recorded in the surface waters. Since the water column in the Bay typically has dissolved oxygen concentrations in excess of eight or nine ppm, this reduction probably results in nearly negligible biological effects. In addition, during dredging with a hydraulic cutterhead or hopper dredge without overflow and during barge disposal with material which has been clamshelled and retains its cohesion, oxygen reductions are even less because of limited sediment-water interaction.

At the bottom, dissolved oxygen reductions were much more pronounced during both dredging and disposal because of increased sediment loading and interaction with the water mass. Dredging operations decreased oxygen levels by three or four ppm and disposal by as much as six ppm as a result of the more intense loading occurring almost instantaneously during release. Typically four to eight minutes were required for the oxygen concentration to return to ambient conditions.

Organisms residing in the upper water column,e.g. plankton and fishes, would probably experience respiratory stress if subjected to the conditions which are generated near the bottom. However organisms which live in close association with sediments are offered some protection by their avoidance reactions, particularly fish and active invertebrate species, or by their innate high tolerance for low oxygen levels. A fish experiencing respiratory distress will begin random movements which may carry it back into oxygenated waters. In bivalves protection may be effected by temporary cessation of pumping activities until the adverse

condition discontinues. In a laboratory experiment, three invertebrate species (Mytilus edulis, Crangon nigricauda, and Synidotea laticauda) and two fish species (Morone saxatilis and Cymatogaster aggregata) from San Francisco Bay were found to be able to tolerate oxygen concentrations of two ppm at eighteen degrees centigrade for several hours to several days (Appendix G). These test organisms were juvenile and adult animals which might be less sensitive than larvae or eggs. But larvae and eggs are part of the plankton in the upper water column where the dissolved oxygen effects of dredging and disposal are much less severe.

The ability of organisms to tolerate low dissolved oxygen levels helps to insure that they do not succumb to asphyxiation during the brief durations of oxygen reductions caused by dredging or disposal. However, sub-lethal effects such as impairment of reproduction or feeding which may occur during summer months when oxygen availability is low are not known. Additionally, if operations take place near sensitive habitats, such as shellfish beds, the persistence of oxygen reductions, although intermittent, causing adverse biological effects when combined with other synergistic adverse effects such as high suspended solids or toxicant loading is not known.

SUSPENDED SOLIDS LOADING

During the periods when sediments are excavated or disposed, a fraction of the sediment is lost to the water column. To ascertain the extent of the adverse effects on San Francisco Bay species a laboratory study was conducted (Appendix G). This research evaluated the impact of the presence of fine mineral particles in the water column on Bay macrofauna. A unique facility providing large aquaria with open, once-through flow of water with desired suspended solids concentrations was employed. Two types of commercially processed clay minerals were used as the experimental material. Initial screening was performed with kaolin, a uniform, low-abrasion particle. Eighteen species of fish and invertebrates were subjected to elevated concentrations of this material to determine their sensitivity. The most sensitive organisms were selected for more intensive study using bentonite clay. This clay is significantly more abrasive or injurious than kaolin because of its size (smaller) and jagged, irregular surfaces. In addition the material showed a high similarity with the fine sediment dredged in north Bay both in size distribution and mineralogy. Subsequent studies with bay mud have shown that the effects of suspended bentonite and natural sediments under comparable conditions are approximately the same (13).

The bentonite experiments were conducted in a stepwise manner beginning with studies of the lethal effect of bentonite at two temperatures (10°C and 18°C). This was followed by a set of tests on the

effects of suspended bentonite at two reduced dissolved oxygen levels (2 ppm and 5 ppm) while temperature was held constant. Finally a multifactor experiment was conducted in which suspended bentonite, temperature and dissolved oxygen were varied simultaneously. Each experiment was run for approximately ten days.

Based on the results of the kaolin tests, six species were selected for the more intensive bentonite experiments. The organisms chosen were: the bay mussel, Mytilus edulis; the polychaete Neanthes succinea; sand shrimp, Crangon nigricauda; the amphipod Anisogammarus confervicolus; the shiner perch, Cymatogaster aggregata; and striped bass, Morone saxatilis. When A. confervicolus could not be found in sufficient numbers, it was replaced in the dissolved oxygen and multifactor experiments by the isopod Synidotea laticauda. The English sole, Parophrys vetulus, was included in the temperature experiment but was replaced in the remaining experiments by M. saxatilis. These species are widely distributed in the Bay and are of considerable ecological importance. Taxonomically none are related at the level of Order and most represent even more widely separated groups. The results of the multifactor experiments are shown in Figures 25 to 29 for all species except the polychaete N. succinea. The experiments with N. succinea showed no correlation of increasing suspended solids concentration with mortality. Control mortalities were fairly high, and while more deaths occurred in the test aquaria, they followed no discernible pattern.

The lethal concentration of suspended bentonite for 2-3 centimeter bay mussels, Mytilus edulis, was much lower than that for large mussels (10 cm). Survival was greater at saturated dissolved oxygen than at 5 ppm or 2 ppm, but little difference was apparent between the reduced levels. The short-term oxygen consumption of M. edulis in suspensions of bentonite was inversely correlated with concentration.

Under conditions of low temperature and saturated dissolved oxygen, survival of 3-5 centimeter sand shrimp, Crangon nigricauda, was high, even in high concentrations of suspended bentonite. Survival was lower at summer temperature, even at saturated oxygen levels. Decrease in dissolved oxygen from saturation to 5 ppm dramatically reduced the tolerance to suspended bentonite.

The isopod Synidotea laticauda suffered few mortalities in the experiments. The plots of survival versus exposure time showed no striking differences in effects of the various conditions except that survival was lowest at 44 grams per liter, 5 ppm dissolved oxygen and 18°C. An analysis of variance confirmed that none of the experimental variables had a statistically significant effect on the length of survival.

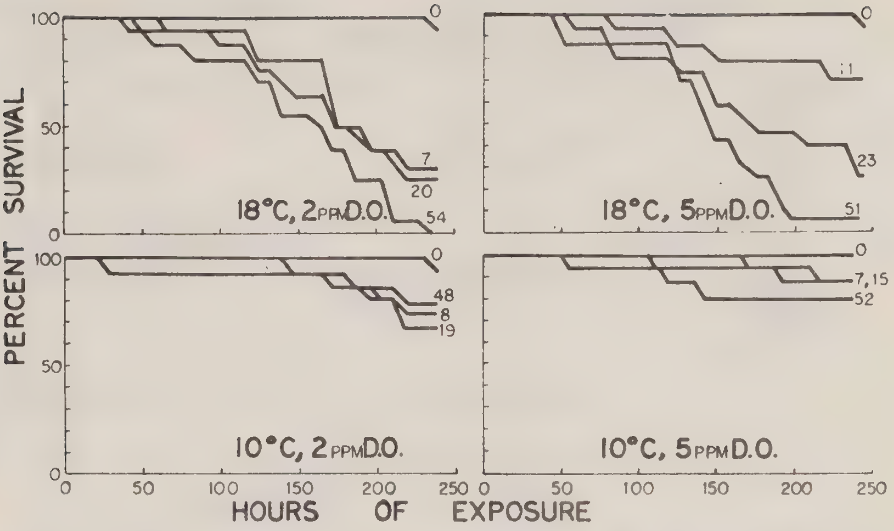


FIGURE 25 SURVIVAL - MYTILUS EDULIS WITH BENTONITE, GM/L

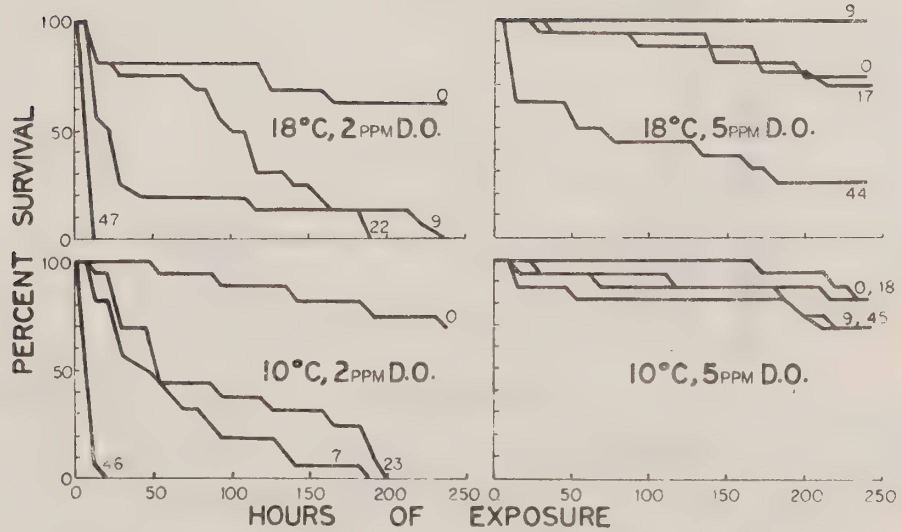


FIGURE 26 SURVIVAL - CRANGON NIGRICAUDA WITH BENTONITE, GM/L

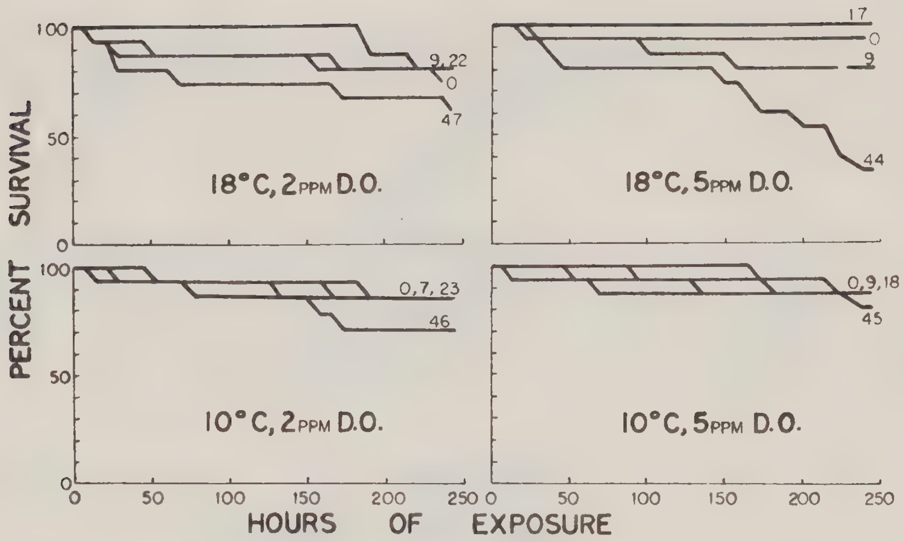


FIGURE 27 SURVIVAL - SYNIDOTEA LATICAUDA WITH BENTONITE, GM/L

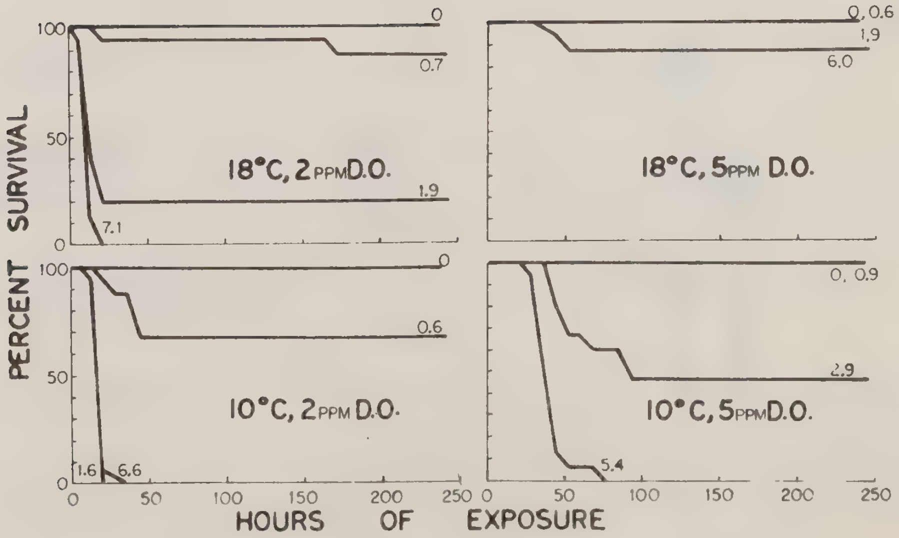


FIGURE 28 SURVIVAL - MORONE SAXATILIS WITH BENTONITE, GM/L

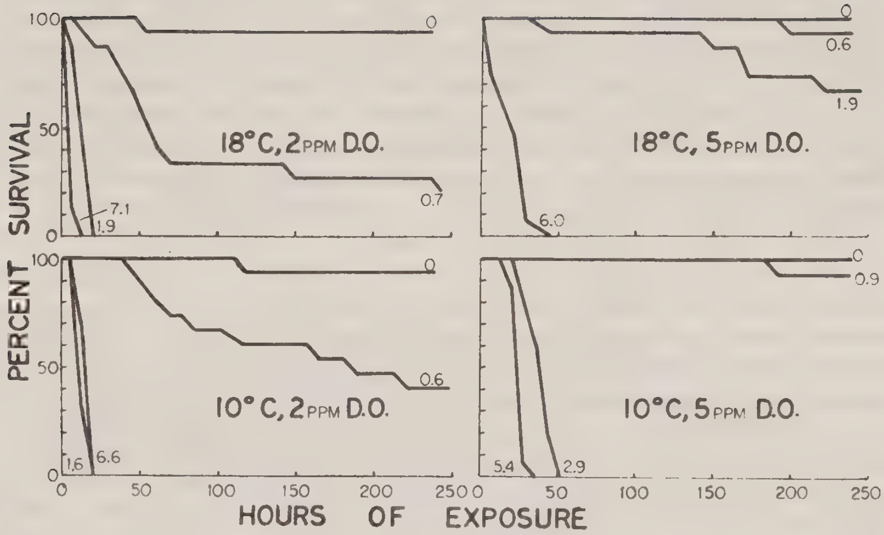


FIGURE 29 SURVIVAL - *CYMATOGASTER AGGREGATA* WITH BENTONITE, GM/L

The fingerling striped bass, *Morone saxatilis*, were killed at lower suspended bentonite concentrations than any of the invertebrates tested. Survival varied inversely with suspended bentonite concentration and directly with dissolved oxygen and temperature. These factors were shown to interact in a complex, non-additive manner to reduce survival.

The most sensitive of the test organisms to suspended bentonite were 6-8 centimeter shiner perch, *Cymatogaster aggregata*. As with *M. saxatilis*, increasing suspended bentonite concentration and decreasing dissolved oxygen and temperature combined in a complex manner to reduce survival. The slightly lower mortality of both species of fish at higher temperature was in contrast to all the invertebrates.

In general tolerance to suspended bentonite seemed to be correlated with the normal habitat of the organisms, but no phylogenetic correlations were apparent. No species living primarily in close association with mud bottoms was found to be sensitive. All sensitive test species were either invertebrates occurring predominantly on sandy bottoms or in fouling communities, or fish not intimately associated with the bottom. Many tolerant species also were found from these habitats.

Direct application of the laboratory results to dredging and disposal activities is not possible. During field operations, elevated suspended solids concentrations exist in the water column for periods of minutes, not days. The solids concentration is intermittently increased with the periodicity dependent on the project and the type of equipment, although a hydraulic cutterhead with aquatic disposal could approach the continuous loading condition generated in the laboratory. This type of operation is extremely uncommon in the Bay. More commonly, Bay operations are performed by the hopper dredge or clamshell dredge with barge disposal.

The hopper dredge disturbs a project area for approximately twenty minutes of a one hour cycle-time. During this time various areas are discontinuously subjected to resuspended sediments generated by draghead benthal disruption and overflow. At the bottom, solids concentrations of about two grams per liter are created for several minutes before redeposition occurs. In the upper water column loadings of approximately a half gram per liter are initially produced and elevated levels (0.2 gm/l) can exist for ten to twenty minutes. The remainder of the hour while the dredge is out of the area in transit to and from the disposal site, the suspended solids concentration is at or near ambient levels.

The suspended solids loading created by the clamshell dredge in a project area is in about the same range as that created by the hopper dredge. However since the dredge does not work with the same degree of mobility as the hopper dredge, the elevated solids levels will exist for longer durations at a specific locale. Depending on the rate of forward dredge movement, durations may vary from several hours to a day.

During release of a slurry from either a hopper dredge or barge, a bottom density flow can occur. The suspended solids concentration near the bottom may pulse at ten to twenty grams per liter for approximately fifteen minutes with the succeeding reduction to background levels requiring an additional fifteen minutes. The minimum time cycle for disposal is about one hour.

Assuming that these suspended solids concentrations are sustained continuously instead of intermittently and temperature and dissolved oxygen levels are at their most stressful condition for the respective test organism, indirect application of the laboratory study showed it would be several hours before the first death. Since these conditions are not maintained in the field, the data implies that these species, and by inference all the species tested, would be able to survive the suspended solids concentrations generated by Bay dredging and disposal activities, although individuals may be killed.

Although organisms may be able to survive the initial impacts of bottom disturbance and associated high suspended solids concentrations, there is a potential for secondary adverse phenomena following the direct interaction between the equipment and the sediment. In the channel, further biological stress may result if a fluff layer is created.

This layer may cause problems by subjecting non-motile species to long periods of high suspended solids and low dissolved oxygen. Filter feeders may have their gills clogged, and epibenthic species may fatigue from having to swim for long periods until consolidation of the sediment occurs. In the disposal area high density mud flows may follow impact of the released material with the bottom. These mud flows typically have suspended solids concentrations greater than ten grams per liter and extremely low dissolved oxygen levels. The period of time necessary for consolidation varies from hours to days, thus creating a period in which the environment would be extremely stressful for benthic and epibenthic organisms.

The potential of impacts from high suspended solids concentrations might be reduced by limiting operations to winter periods. The results of the laboratory study indicated that the biological effects of suspended solids would be less severe in winter than in summer (App. G). The typically higher dissolved oxygen levels would increase the survival ability of all species studied. Low temperatures would increase the suspended solids tolerance of the invertebrates, but slightly decrease that of the fish. However, this slight reduction would likely be offset by the increased tolerance at high dissolved oxygen levels. In winter there would also be fewer actively reproducing adults and fewer larvae and immature stages present, which may or may not be more sensitive to lower suspended solids concentrations than the adults studied during these laboratory experiments.

UPTAKE AND ACCUMULATION OF TOXICANTS

The sediments act as a reservoir for the majority of constituents with concentrations in the parts per million range whereas the overlying waters have concentrations in the sub-parts per billion and parts per billion range. The scavenging effect of clay and silt particles during the sedimentation process is responsible for the higher levels of trace elements, chlorinated and petroleum hydrocarbons, etc. in bottom deposits. Another constituent, hydrogen sulfide, can be generated following deposition and consolidation of sediment particulates.

When sediments are left undisturbed for long periods with decomposable organic matter available, bacteria (Desulfovibro sp., etc.) will use sulfate as a hydrogen acceptor to form hydrogen sulfide. This compound is extremely toxic to organisms. It not only combines rapidly with oxygen to reduce the available level for respiration but adversely affects fish egg hatching as well as fry and juvenile survival. The generated hydrogen sulfide quickly reacts with available trace elements, particularly iron, to form insoluble compounds which lack these acute toxic properties. When iron is present in the sediments, the concentration of toxic sulfide compounds may remain at low levels (below 1 mg/l) (14). Serne and Mercer (Appendix F) found the free hydrogen

sulfide values in the interstitial waters of San Francisco Bay sediments were below their detection limits (<0.05 ppm) even though the total sulfide concentrations ranged from 1,000 to 3,000 ppm. They suggested that if hydrogen sulfide was formed in the interstitial water it was quickly transformed to insoluble complexes before building up to measurable levels. The sediments in the Bay have a reservoir of approximately 5 per cent iron, thus sufficient quantities of this metal are available to participate in complexing reactions to dissipate potential hydrogen sulfide production. Accordingly, in San Francisco Bay this toxicant is not considered to be a significant problem during dredging or disposal operations.

Other chemical reactions occurring during Bay dredging and disposal activities are potentially biologically important and include mobilization of trace elements, release of hydrocarbons, and release of ammonia. All of these phenomena have been observed in both the laboratory and the field. However, these demonstrated changes in water quality did not produce analogous effects in impacted test organisms during two field experiments.

A study (Appendix H) was conducted during dredging operations between September 1973 and May 1974 to determine whether these operations released heavy metals from the dredged sediments resulting in elevated concentrations of the metals in adjacent sediments or invertebrate populations. The concentrations of the metals silver (Ag), cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), selenium (Se), zinc (Zn) and the element arsenic (As) were monitored in surface sediments and the invertebrates Macoma balthica, Neanthes succinea, Ampelisca milleri, and Ischadium demissum collected from stations adjacent to and outside of the dredge zone before, during, and after two dredging periods. Mussels, Mytilus edulis, were transplanted from Tomales Bay to stations inside and outside of the dredge zone in Mare Island Strait. Changes in the concentrations of the above metals were monitored and compared with the metal concentrations observed in native mussels in Mare Island Strait and at Tomales Bay.

Lead concentrations were monitored in water and suspended particulates collected before, during and after two dredging periods. Analyses were performed on raw water aliquots and on water that was centrifuged to separate suspended particulates.

A laboratory study was conducted to determine the effects of salinity and metal concentration on the uptake and accumulation of the chloride salts of the metals Ag, Cd, Cu, Pb, and Hg by M. balthica. The clams were exposed to three salinities (4.8, 12.5 and 25 parts per thousand) during this nine day experiment.

Unfortunately, the two periods of dredging activity coincided with the two periods of heaviest rainfall for the year. Salinity decreased markedly in Mare Island Strait during the period of study with the lowest salinities being observed at stations further up the strait.

Metal concentrations in sediments and invertebrates fluctuated during the period of study. With the exception of nickel concentrations in N. succinea, no significant changes in metal levels were associated with dredging activities although significant uptake and desorption did occur throughout the study area. The changes in nickel were significantly greater at stations outside of the dredged zone suggesting that dredging may have inhibited nickel accumulation in this species.

Concentrations of the metals Cd, Cu, Hg, Ni, Pb, Se, and Zn were generally two to three times higher in native M. edulis than in Tomales Bay controls during this period. However, metal concentrations were not significantly different in M. edulis transplanted to stations within the dredge zone than in mussels transplanted to stations outside of the dredging area during any collection. Mussels transplanted to Mare Island appeared to accumulate the metals Cu, Ni, and Zn above Tomales Bay control concentrations. However, no metal was accumulated by transplanted mussels to the levels observed in mussels native to Mare Island.

The concentrations of lead in uncentrifuged water and in suspended particulates increased during the first dredging period. Comparable changes were not observed during the second dredging period suggesting that the observed changes resulted from surface runoff during the first rain storm.

The results of the nine day laboratory study showed that the greatest uptake and accumulation in M. balthica of the chloride salts of the metals Ag, Cd, Cu, Hg, and Pb occurred with the highest concentrations of these metals in the lowest salinity water. Figure 30 shows the results for mercury salts. The greatest desorption of the metals Ni, Se, Zn and element As during the nine day laboratory study occurred in the clams exposed to water with the highest salinity.

The increases in concentrations of the metals Ag, Cu, Hg, Zn and to a lesser extent Pb in M. balthica at all stations after each period of dredging and a general increase in these concentrations during the study, correlate well with the results of the laboratory study which showed the greatest uptake of metals to occur at the lowest salinity. The heavy rains during each of the two respective dredge periods resulted in marked decreases in salinity at those times and a general decrease in salinity during the study.

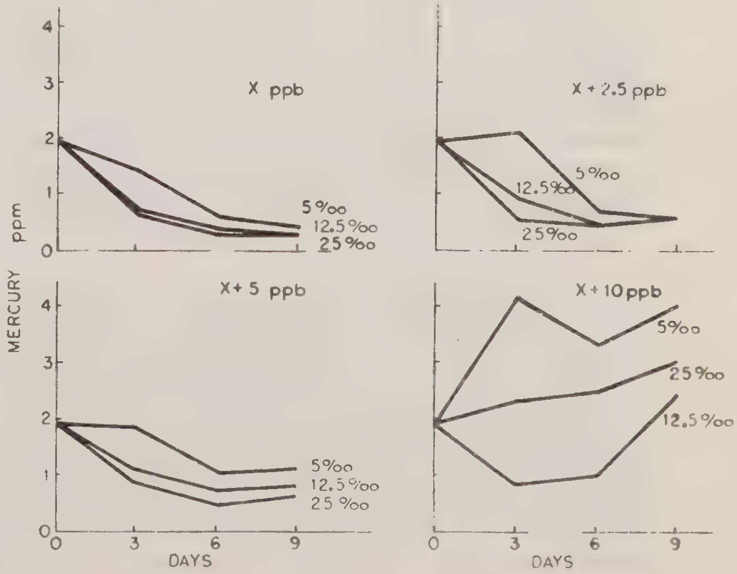


FIGURE 30 MACOMA BALTHICA - MERCURY UPTAKE

The data obtained during the field studies indicate that the collection and analytical methods employed during this study were reproducible and sensitive enough to detect small natural fluctuations in the concentrations of these elements. If fluctuations occurred as a result of dredging activities, the changes were less than these small natural fluctuations and/or of short duration.

A second study (Appendix I) was conducted during a disposal operation to ascertain if chemical reactions resulting from the operation increased the availability of selected toxicants or in other ways caused significant adverse biological effects. The investigation was conducted during the release of 10,000 cubic meters of "polluted" sediments at an experimental disposal site in Central San Francisco Bay. Six stations were established at this location. Three inner stations were 100 meters from the impact point of the release and three outer were 300 meters from the center. The outer stations were situated at a sufficient distance to be used as reference stations receiving no or at most a diminished effect from the disposal. The concentrations of twelve trace elements (Ag, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, and Zn) were monitored in sediments, suspended and settled particulates, selected benthic invertebrates (Macoma nasuta, Pectinaria californiensis, Stylatula elongata, Tritonia diomedia, Glycerna americana and G. robusta) and transplanted mussels, Mytilus edulis. The mussels were placed in Nytex bags and suspended 1, 4 and 7 meters off the bottom at each station. All stations were in approximately 10 meters of water. Concentrations of chlorinated hydrocarbons (DDT, DDD, DDE and PCB as Aroclor 1254) were also monitored in sediment, water and mussels before, during, and after the releases. Water quality parameters (temperature, salinity, dissolved oxygen, pH, nitrate and ammonia nitrogen) were monitored during the disposal operations as were the solute concentrations of Cd, Cu, Hg and Pb. The water quality parameters were also monitored during 24-hour collections one month prior to and one month following the disposal operations, and the metals only following the operations. The disposal operation took place over a 42-hour period (3-5 February 1975) with the seven releases from the hopper dredge HARDING being synchronized with slack water conditions. Following each release, water and suspended particulate samples were collected for immediate and future analyses. In addition further laboratory studies were performed with Macoma nasuta, Pectinaria californiensis, and Mytilus edulis.

The experimental disposal operation did not affect trace element concentrations in the benthic invertebrates examined nor in mussels transplanted to the disposal area. Chlorinated hydrocarbon concentrations in disposal site mussels fluctuated slightly during the period of study and only p, p'-DDE levels in mussels appear to have been affected by the disposal operation. DDE levels decreased significantly more in mussels at stations outside of the immediate disposal area and at other central bay locations than in mussels immediately adjacent to the disposal center. This effect was not apparent by the next sampling period, one month later. Subsequent analysis showed that the disposal operation had no effect on aromatic petroleum hydrocarbon levels in the mussels. Comparable results were obtained for the aliphatic fraction (15).

The laboratory study showed that: (a) mercury in solution was accumulated from sea water at all concentrations by M. nasuta, P. californiensis and M. edulis. (b) little, if any, Pb was accumulated by P. californiensis from sea water. Control animals of this species desorbed lead during a 15-day experiment. A slight uptake of Pb was observed in M. nasuta when these animals were exposed to the highest Pb concentrations tested. Pb was accumulated by M. edulis at all concentrations tested with desorption occurring in the control mussels. (c) Cadmium concentrations decreased in P. californiensis at all concentrations tested. Cadmium was accumulated by M. nasuta exposed to high and medium concentrations, with the Cd content of control animals remaining constant throughout the experiment. M. edulis accumulated Cd linearly with time at all exposure concentrations. The Cd content of control mussels was constant throughout the experiment.

Based on these two field experiments, Bay dredging and disposal activities were found, under the conditions of the experiments conducted, to redistribute contaminated sediments without resulting in increased contaminant availability. Fluctuations in the concentrations of the test elements were highly correlated with each other in sediment, invertebrates, suspended and settled particulates, although element levels within any one component were not correlated with element levels in any other component. The high correlation among trace elements within each component suggests that only one or a few parameters may control trace element fluxes in San Francisco Bay.

Although some constituents exhibit varying degrees of release to the water column during the discharge of dredged sediment, these releases are so small (parts per billion range) and of such short durations (minutes to a few hours) that their actual availability for direct biological uptake is highly localized. Outside of the zone being directly influenced by the operation, concentrations of the released constituents are tremendously decreased because of dilution with uninfluenced waters. Dilution factors on the order of a thousand to ten thousand can occur in a matter of a few hours. However, if the released constituents readsorb on organic and inorganic sinks from which biotransfer is possible, then increased constituent availability may result in increased organism accumulation on a long-term basis from the redeposited sediment.

Luoma and Jenne (27) found uptake of cadmium by a deposit feeding clam, Macoma balthica, from San Francisco Bay sediment, hydrous-iron oxide particulates (which lacked organic coatings) and a solute pool (solution). No detectable uptake occurred through ingestion of either labeled organic detritus or particulate hydrous-iron oxide which had been coprecipitated with cadmium and coated with organic material. In general, it was found that sediment ingestion presented a relatively inefficient mode for cadmium uptake with steady state concentrations in the clam never exceeding 15 percent of the bulk sediment concentration.

Other investigations with this species of clam have shown that silver is also more available from inorganic substrates of sinks than from organic matter; however, for zinc the inverse seems to be true (28). Gut acidity would probably be sufficient to break down some organic compounds (humic or fulvic acids, etc.) which typically have scavenged any available heavy metals. These materials are produced as breakdown products or by-products of metabolic activities. The humic and fulvic acids are derived from herbaceous matter which degrades under bacteriological attack. Other organic molecules capable of complexing come from organisms' excretions, terrestrial detritus, and municipal-industrial discharges. These materials move through the water column until they are removed by ingestion or flocculation/aggregation and settling. During the period in the water column, the molecules will bond with other molecules or ions depending on respective charges. If ingested, the molecular chain or network will be broken down and the elements may be incorporated into the body fluids via passive or active uptake or voided. The elements taken up can be used in the cellular operations, stored or ejected after a period of time. Those elements that are stored may be concentrated to such a degree as to be toxic to the organism itself or to other organisms that might eat it. The exact level at which elements are toxic varies between species and even between individuals and life history stages within the same species. If the organic compound settles before ingestion by filter feeders, it can be ingested by deposit feeders and the same gut processes, more or less, occur. If it is not ingested by macro-organisms, it will be attacked by micro-organisms. The forms, principally bacteria, can break down the organic molecule, release the elements for future chemical reactions or uptake by organisms.

As previously mentioned, of the trace constituents monitored during the experimental disposal operation, only changes in p,p'-DDE levels in M. edulis appeared to be related to the disposal operation. Concentrations of p,p'-DDE decreased significantly more in mussels at removed stations than in impact station mussels. This difference was possibly the result of increased DDE availability during the disposal period. However, this effect did not persist after the disposal period since, one month later, chlorinated hydrocarbon levels were equivalent at all stations.

Young (16) working in the Southern California Bight found that contamination of sediments by chlorinated hydrocarbons appeared to have serious implications regarding the persistence of contaminants such as DDT and PCB in an aquatic ecosystem. Although the predominant industrial source of DDT to the Joint Water Pollution Control Plant sewer system was cut by more than a factor of 15 between Spring and Fall of 1970, the median concentrations in both bottom sediments around the outfalls, and in a flatfish (Dover sole) living in these sediments, decreased at much slower (and equivalent) rates. Effective total DDT

and total PCB inputs into the waters of the Bight in the six months prior to the May 1972 and February 1975 collections were estimated. For total DDT, over this interval the estimated input decreased by a factor of 5.8 while the median tissue concentration for Dover sole decreased by a factor ot 1.5. The median surface sediment concentration of total DDT in the monitoring zone also decreased by a factor of 1.5 between 1972 and 1975. For total PCB, the estimated input decreased by a factor of 12.0 over this interval while the Dover sole median concentration decreased by a factor of 1.9. In comparison, between 1972 and 1975 the median surface sediment concentration of PCB in the monitoring zone decreased by a factor of 1.6.

Nathans and Bechtel (17) studied the availability of sediment-sorbed pesticides (DDT and analogs) to benthos with particular emphasis on deposit-feeding infauna. They found that when exposed to sediments containing DDT, Tubifex tubifex, Capitella capitata and Nephtys californiensis accumulated the pesticide. Maximum levels of DDT accumulation were reached by T. tubifex and by C. capitata within 30 days, whereas a maximum level was attained by N. californiensis at about 70-80 days. A steady state indicating the occurrence of regulation was attained between pesticide concentrations in the sediment and in the organisms, precluding long-term gradual increases of DDT and its metabolites in their body tissues. Bioaccumulation factors calculated for T. tubifex and for N. californiensis were less than 10 and for C. capitata between 50 and 100, when related to the total sediment.

Thus, although the increases found in the chlorinated hydrocarbon concentration in the water column did not seem to affect tissue levels, except possibly in the case of p,p'-DDE, there is a potential for long-term increases from the redeposited sediment.

BIOSTIMULATION

The phosphorus-nitrogen ratio is important for assessing the eutrophication of surface waters. A rough estimate is that algal cells need about three parts phosphate (one part of phosphous) to 15 parts of nitrogen or a "utilization" ratio of 1 to 5. Previous work in the Bay found the ratio to be 1.4 to 1 which indicates that phosphate is in excess of algal requirements to such a point that fluctuations in the concentration would have no effect on algal growth (18). Nitrogen available for algal incorporation has also been found in excess. Studies in Suisun Bay during the periods of maximum microplankton concentration showed that no more than 17 percent of the available nitrogen was utilized by the algal cells (18).

Nitrogen, in the form of ammonia nitrogen, besides having a stimulatory effect can also have a toxic effect. Organic nitrogen undergoes changes of decomposition from complex proteins through amino acids to ammonia nitrogen, nitrites and nitrates. Nitrates, primarily, are then utilized in the synthesis of new plant and animal tissues. This "nitrogen cycle" is dependent on bacterial action for the decomposition, and on photosynthesis for the reconstruction of organic nitrogen. To algae and other organisms, the total concentration of nitrogen is not as important as its chemical form. Organic nitrogen, amino acids and ammonia may inhibit biological growth whereas nitrates usually stimulate phytoplankton. Some plant forms, however, are able to metabolize ammonia and nitrites and, therefore, are not dependent on complete nitrification. Ammonia gas, produced by decomposition, reacts with water to form ammonium hydroxide. This, in turn, readily dissociates into ammonium and hydroxyl ions. The ratio of ammonium ions to ammonium hydroxide is a function of pH. At common bay pH's most of the ammonia in the water exists in the form of ammonium ions. As pH increases the reaction tends to favor the concentration of ammonium hydroxide. Toxicity is directly related to the concentration of undissociated ammonium hydroxide in solution. As pH increases the same total concentration of ammonia will become more toxic. Dissolved oxygen and carbon dioxide concentrations influence the toxicity of ammonia. As the oxygen concentration decreases, the carbon dioxide excreted across the gill surface of organisms proportionally decreases. In high dissolved oxygen tensions, the gill is releasing sufficient quantities of carbon dioxide to reduce the pH adjacent to its surface, thus ammonia is in the ionic form. As gas transport decreases, the pH rises and more un-ionized ammonia contacts the surface. This leads to increased toxicity of the ammonium in solution. On this basis the 1972 Water Quality Criteria "Blue Book" recommended that concentrations of un-ionized ammonia not exceed 0.4 mg/l to avoid hazards to marine biota (12).

Fertilization of Bay waters via release of nitrogen and phosphorus during resuspension and dispersal of dredged sediments could be occurring. Anderlini et al (App. I) recorded increases of nitrate nitrogen to a maximum of 1.9 mg/l following an experimental disposal operation in San Francisco Bay. Ambient concentrations were typically 0.4 mg/l, giving an increase of almost five times. However, since the nutrient reservoir in North San Francisco Bay presently seems to be in excess of algal growth requirements (19), this additional nutrient loading has a low potential for stimulatory effects. A more pertinent problem is the release of ammonia from disturbed sediments. Chen et al (10) found tenfold increases in the ammonia level in a confined water mass when sediments were introduced. Lee et al (20) performed elutriate analyses with channel material and found dramatic increases in the concentration of ammonia following the shake and settling. Ammonia concentrations increased at higher sediment to solution ratios. Four sediments were

tested from various parts of the country. The mean concentration was 0.45 mg/l un-ionized ammonia. The maximum concentration was 1.18 mg/l obtained with Houston Ship Channel material. They suggested that, although these were toxic concentrations, field dilution would quickly reduce the ammonia to non-toxic levels. Field observations in San Francisco Bay have shown increases in the ammonia concentration from a background level of 0.03 mg/l to 0.3 mg/l (App. I). Increases disappeared within one and one-half hours due to nitrification and/or dilution. The portion of this ammonia that was un-ionized ammonia was not determined. Most laboratory studies of the toxicity of ammonia to invertebrates and vertebrates have been performed under steady state conditions. Those studies are of little value in assessing the effects of short-term high increases of ammonia on organisms.

ALTERNATIVE DISPOSAL METHODS

During the last century, the periphery of the Bay has been drastically altered for man's needs. To illustrate this point, the historical marshes in 1850 shown in Figure 31 can be compared with the present marshes shown in Figure 32. Large areas have been diked. These areas have been developed as evaporation ponds for the extraction of salt from seawater, converted to farmland for hay production or filled for residential and commercial uses. Open areas around the Bay occur both above and below mean higher high water, thus there is a potential to return many areas to wetland conditions. Alternative disposal methods discussed in this section include contained sites for the development of either fastlands or wetlands.

LAND DISPOSAL

Potential land disposal areas around the Bay area were mapped (Appendix J). The following criteria were applied during the mapping for identifying suitable sites:

- Areas must be larger than 80 hectares. This was to identify and evaluate sites capable of accommodating disposal from dredging on a large scale, long-term basis.

- Sites must not encompass public wildlife refuges, recreational areas or critical wildlife habitats.

- Areas should be below plus 15 meters mean sea level as a transportation consideration and above mean higher high water as a recognition of potential wetland use.

- Areas must not have existing development.

- Areas should be within 97 kilometers combination land-water distance of any dredging site.

Other considerations included excessive slopes, interference with flood plain management, seismicity, drainage, site accessibility, load capacity and subsidence. Sand and gravel quarries were considered but eliminated because of potential groundwater contamination.

FIGURE 31 HISTORICAL MARSHES - 1850

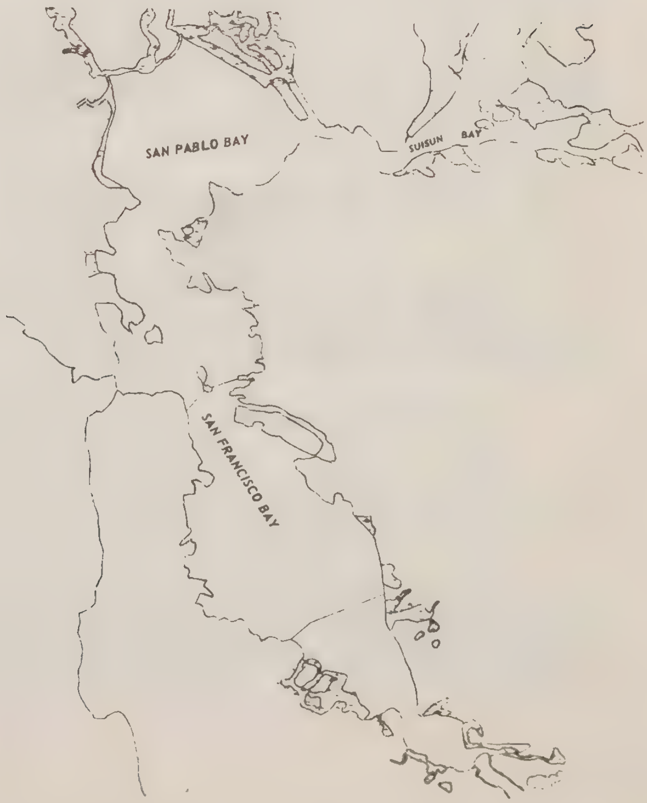


FIGURE 32 EXISTING MARSHES - 1975

Fifteen potential sites were identified in the process. The sites are listed in Table 13 and shown on Figure 33. Each of the sites is discussed in detail in Appendix J. It should be noted that not all of the sites are entirely above mean higher high water. Portions of some sites are slightly below mean higher high water and were included on a judgment basis. The placing of environmental constraints on the various potential sites is a judgment factor. Agencies in the Bay area were requested to place ratings on each of the fifteen sites.

Ratings were received from four agencies, U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, California Department of Fish and Game, and the California Regional Water Quality Control Board San Francisco, and are listed in Table 13. Concerns expressed in developing the various ratings included:

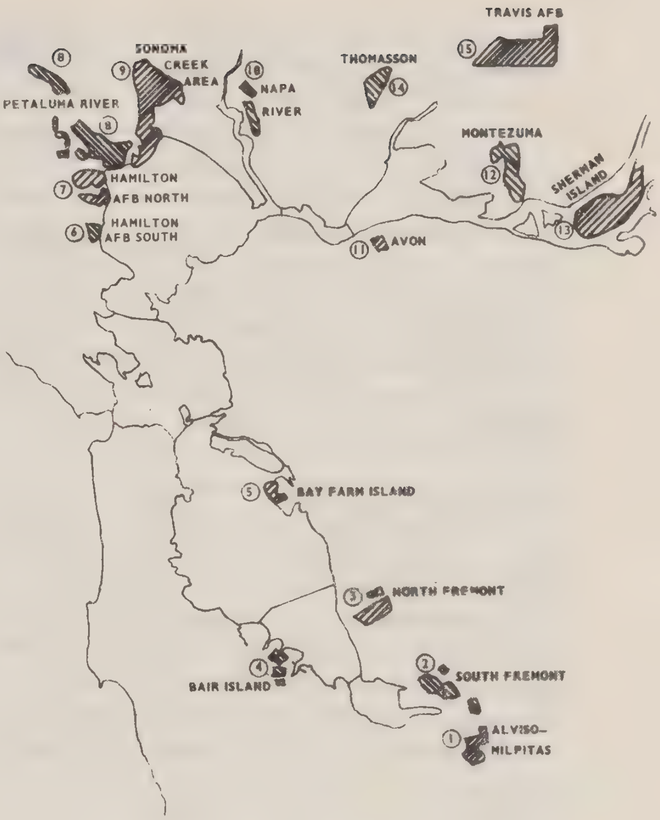


FIGURE 33 POTENTIAL LAND DISPOSAL SITES

- portions of area are restorable to tidal action;

- area has varying degrees of valuable wildlife habitat;

- area is a fish and wildlife buffer zone;

- land use changes must be considered;

- access to area has potential for damaging adjacent wetlands;

- water quality of effluent including salinity changes may be a problem;

- adverse impacts may occur to adjacent areas.

Only two of the fifteen sites were considered not to have major problems or not to be totally eliminated. All sites were listed as requiring wildlife mitigation. Restricted land use or dedication to wildlife habitat was stipulated for all sites. The least objectionable is Site 13, Sherman Island.

TABLE 13

POTENTIAL LAND DISPOSAL SITES

Site	Number	Area (hectares)	Capacity (10^6 m^3)	Rating of Site Problems 1/ EPA	USF&WS	Cal F&G	CRWQCB-SF
South Bay							
Alviso-Milpitas	1	1,030	31	2	3	1	1
South Fremont	2	790	24	2	3	1	1
North Fremont	3	730	22	3	3	3	1
Bair Island	4	1,010	15	2	1	1	1
Central Bay							
Bay Farm Island	5	360	11	2	3	2	2
North Bay							
Hamilton AFB South	6	470	14	2	2	2	1
Hamilton AFB North	7	1,560	47	2	2	2	2
Petaluma-Sonoma-Napa							
Petaluma River Area	8	3,480	106	2	2	2	2
Sonoma Creek Area	9	4,290	131	2	2	2	1
Napa River	10	500	15	2	3	3	3
Suisun Bay-Delta							
Avon	11	160	5	3	3	3	3
Montezuma	12	1,210	34	2	2	1	2
Sherman Island	13	4,050	242	3	4	3	3
Fairfield-Dixon							
Thomasson	14	1,740	53	2	2	1	1
Travis AFB	15	3,240	99	3	3	2	4

1/ 1. Should not be considered
2. Major problems
3. Some problems
4. No problems

As a representative island of the Delta, Sherman Island, the closest to dredging sites, was chosen for analysis for comparison with other alternative disposal methods. Other adjacent islands, such as Jersey, Bethel, Bradford, Webb, Twitchell and Brannan, would be very similar but with a longer transport. The soil of the Delta islands is sediment and peat, and provides productive agricultural land. In addition to their high values from an agricultural viewpoint, the Delta islands are a habitat for many forms of wildlife and are used extensively by hunters. The adjacent sloughs and rivers form an important fishery resource, and fishing, as well as other water-related activity, is an important attraction. The southwestern boundary of the Sherman Island site is adjacent to the State Game Management Area and, consequently, the effect of this use on wildlife values in the areas would have to be carefully evaluated. The addition of the dredged sediment would reduce the danger of flooding by a simple increase in average elevation, since the island is presently entirely below MHHW. Deposition of the sediment would also probably result in a reduced rate of

oxidation of peat deposits, with a consequent reduction in the rate of land subsidence. The increased loading of the site, however, may more than offset the reduction in subsidence due to the oxidation. The loading may also cause mudwave shallowing of adjacent sloughs, thereby altering water circulation patterns. The potential for filling sloughs during rupture of a dike during earthquakes is also present. Control of effluent to the adjacent river system would require careful study because of both the introduction of saltwater in the freshwater system and the mobilization of contaminants. Increased salt loading would adversely affect water supply, irrigation and fisheries. Several proposals have been made to combine various wastes including dredged sediments, garbage compost, sewage sludge and others to raise the elevation of the Delta islands in addition to solving the waste disposal problems.

If dredged sediment can be considered a potentially useful resource rather than a "spoil" or "waste," then land disposal of dredged sediments could become an attractive alternative. Land disposal sites could possibly be used for agriculture, recreation or wildlife habitat. The land disposal studies were aimed at identifying potential sites along with a preliminary assessment of technical and environmental considerations. Because of identified technical difficulties and adverse environmental effects which may be involved, extensive land disposal for maintenance dredging projects does not appear to be a viable alternative to aquatic disposal at this time.

WETLAND DEVELOPMENT

Detailed research into the basic ecology of salt marshes began to receive emphasis nationally during the early 1950's. These early studies demonstrated the importance of marshlands to the estuarine ecosystem. Until the late 1960's, however, little information had been developed about the artifical development of new marshlands.

The restoration of marshlands is a particularly important issue in California, for the State has the dubious distinction of being the Nation's leader in the destruction of marshes and wetlands (29). Since California was admitted into the Union (1850) more than 1,000 square kilometers of wetlands have been diked and filled. In Southern California, only Morro Bay, San Luis Obispo County, retains a significant portion of its tidelands. At one time San Diego's Mission Bay included nearly [illegible] square kilometers of mudflat and marsh. Today, less than 0.2 square kilometers of marsh and virtually no mudflat areas remain in Mission Bay. When the rush for gold began in California, more than 810 square kilometers of marshlands formed the shores of Suisun Bay, San Pablo Bay, and South San Francisco Bay. Today, fewer than 325 square kilometers of marsh remain.

Unlike the Atlantic coast, the Bay is subject to the Pacific coast mixed, semi-diurnal tidal pattern. Tidal range within the Bay generally increases in the bays inland from the Golden Gate. For instance, the mean tidal range at the Golden Gate is approximately 1.34 meters, whereas, the southern tip of the South Bay (approximately 80 kilometers from the Golden Gate) has a tidal range of 2.74 meters. This broad tidal range, combined with the shallow nature of a large portion of the Bay, results in the regular exposure of extensive intertidal lands. In general, only areas above the mean tide level (MTL) are colonized by vascular plantlife. Within this area between MTL and the highest estimated high water are two dominant vegetative zones: the Spartinetium (consisting primarily of genetic variants of California cordgrass, Spartina foliosa) and the Salicornietium which comprises several representatives of the Genus Salicornia, commonly referred to as pickleweed.

Field planting studies were initiated in May 1974 in the intertidal zone along the north bank of the Alameda Creek Flood Control Channel, South San Francisco Bay to appraise the relative success of various planting procedures (Appendix K). Tidal datum at the site is 1.3 meters at mean tide and 2.4 meters at mean higher high water. Substrate within the testing area was dredged sediment placed by clamshell dredging operations. The sediment was allowed to settle approximately one year at which time (two weeks prior to the planting of the test plots) 0.3 to 1 meter of the surface sediments were removed exposing a new barren face (elevation from 1.8 meters to 3.3 meters, MLLW, sloping toward the channel).

Five planting methods used in the cordgrass test plots were seeding, seedlings, robust rooted cuttings, dwarf rooted cuttings and plugs. Three planting methods used in the pickleweed test plots were seedlings, rooted cuttings and unrooted cuttings. Both fertilized and unfertilized conditions were employed.

Table 14 gives a comparison of cordgrass growth for one and two growing seasons for each of the planting methods. The number of culms (stems) per square meter increased rapidly during the second growing season. If this rapid growth rate continues, plant densities (culms/m^2) in the plug, dwarf rooted cutting, seedling, and seeded plots would be comparable to natural marsh areas (approximately 450 culms/m^2) mid-way through the third growing season. The control and robust rooted cutting plots may require two to three additional years to reach parity with existing marshes.

As anticipated, development of plant cover in the pickleweed plots was more rapid than that observed in the cordgrass plots. By the close of the second growing season even the unplanted pickleweed control plots had exceeded all cordgrass starter types in plant material production with approximately 140 grams per square meter, dry weight. The use of seedlings and rooted cuttings significantly accelerated the process of revegetation above the natural rate. However, the differences between planted and unplanted areas was not nearly as striking in the pickleweed experiments. Even in the absence of artificial encouragement, pickleweed invasion of barren areas appears to be very rapid.

TABLE 14

CORDGRASS - COMPARISON OF CULM ABUNDANCE

OCTOBER 1974 V. OCTOBER 1975

Planting Method	# Culms per m^2 (1974)	# Culms per m^2 (1975)	Factor of Increase
Control	0.07	2.52	36.0
Seeding	3.24	52.22	16.1
Seedlings	3.68	64.74	17.6
Robust Rooted Cuttings	0.99	6.55	6.6
Dwarf Rooted Cuttings	3.79	85.72	22.6
Plugs	5.26	88.13	16.8

The addition of fertilizer to one-half of the test plots produced no significant change in the rate of growth or overall survival of propagules.

A survey was made of potential marshland development areas in San Francisco Bay. Some 500 square kilometers of historic marshlands in the Bay have been diked for salt production, agriculture, and industrial and urban development. As a result of subsidence due to extensive ground-water depletion, wind erosion and consolidation, most of these diked areas are now lower than when they were reclaimed 50 to 100 years ago. The survey indicated that there are approximately 270 square kilometers of diked lands adjacent to San Francisco Bay which still have surface elevations below mean higher high water. In Bay marsh development projects, the depth of fill to achieve desired elevations will seldom exceed two meters and will typically be from 0.5 to 1.0 meters. Theoretically, therefore, 200 to 250 million cubic meters of sediment could be accommodated if total utilization was made of the marsh development disposal alternative. Areas for potential marshes are shown on Figure 34.

Dredging for the development of marsh substrates would generally be conducted by hydraulic dredge with pipeline to the disposal area. The broad tide flats of the Bay would require transfer facilities for use of any other type of dredging operation. Hydraulic slurries of Bay mud may contain more than 90 percent water. To contain the slurry volume during dredging, existing dikes may have to be elevated. Depending upon the dredging rate and the dimensions of the disposal area, more than one meter of freeboard may be required to contain the water-sediment mixture while sediment material consolidates and the resulting surface water is decanted. In general, the bayward dikes in reclaimed areas are more substantial and higher than the inland dikes. The bayward dikes are responsible for protecting the inland areas from the tides and must be substantial enough to resist wave action. Once the exterior dikes are breached, the interior dikes inherit the responsibility for containing the tide waters. Dikes around a marsh development area must be surveyed before breaching so that low and/or weak areas can be identified and corrected. All dikes surrounding the containment area must be of an elevation higher than the estimated highest tide. The height of waves expected in the area to allow for wave overtopping must also be considered. These considerations are of particular importance when adjacent areas are being actively used for salt production or agriculture.

FIGURE 34 POTENTIAL MARSH SITES

As previously noted, the tidal range at Alameda Creek is approximately 2.5 meters and the highest estimated tide is 3.2 meters above MLLW. It was estimated that this dike elevation with freeboard would contain the estimated highest tide and protect adjacent areas from wave over-topping.

Two factors complicate the preparation of the estimate of sediment quantities which can be placed at the site: (1) typically, commercial dredging operations excavate sediment in excess of that which is required by specifications to allow for irregularities created in the bottom and

to assure that the required minimum depth is reached, and (2) there is little information available which compares the density of in-situ sediment in dredged channels with final density of dredged sediment after disposal in terms of final change in volume. During the hydraulic fill operation at Alameda Creek, the amount of excess of non-pay yardage was between five and ten percent of the total yardage. Though the amount of excess dredging, if any, will vary with dredging conditions (depth of cut, type of equipment, and type of sediment), one must recognize the fact that dredging in excess of specifications will probably occur. Sediments in dredged channels in San Francisco Bay typically contain from 85 to 95 percent silts and clays with 5 to 15 percent sand and shell fragments. Sediments in the Alameda Creek Flood Control Channel contained about 95 percent silts and clays. In-situ water content in submerged Bay sediments ranges between 45 and 55 percent. Because of the similarity of dredged sediments and marsh substrates in the Bay with respect to grain size and water content, the assumption that the volume of in-place material to be dredged would be approximately equal to the final disposal volume would probably suffice for most marsh development projects in the Bay. A cursory survey of the topography of the Alameda Creek Pond 3 marsh development site one year after disposal indicated that the average slope within the pond was generally less than 1 vertical on 500 horizontal. This gradual slope was formed as a result of the fluid nature of the hydraulic slurries. Therefore, the vertical range which can be created in a confined disposal area is largely a function of size. Drainage may be promoted and vertical range optimized by locating the discharge pipe near interior dikes.

COST COMPARISON

As part of the evaluation of alternative disposal methods, including alternative open water sites and confined disposal sites, a computer model was developed to compare relative costs (Appendix J). The model assumes an idealized systems dredging with use of equipment site-efficient to the operation and fully utilized.

In addition to the cost associated with greater transport distances, other factors such as type and size of dredging equipment and characteristics of the dredging sites were found to influence the comparative cost. The site characteristics affect the efficiency of the dredging equipment. Table 15 lists twelve dredging sites in the Bay along with their shoaling characteristics.

TABLE 15

CHARACTERISTICS OF SAN FRANCISCO BAY
DREDGING SITES

Site	Shoaling Depth	Coverage	Work Area	Average Face Depth (Meters)
Suisun Bay	Uniform	Spotty	Open	0.9
Mare Island	Wedge	Spotty	Open	1.5
Napa River	Uniform	Spotty	Narrow	0.9
Petaluma River	Wedge	Smooth	Narrow	0.8
Pinole Shoal	Uniform	Spotty	Open	1.2
Richmond L.W.	Uniform	Smooth	Open	0.9
San Rafael Creek	Uniform	Smooth	Narrow	1.1
W. Richmond Channel	Wedge	Smooth	Open	0.9
Richmond Harbor	Uniform	Smooth	Open	0.9
Oakland	Wedge	Spotty	Open	0.9
San Francisco	Wedge	Smooth	Narrow	0.9
Redwood City	Wedge	Smooth	Open	0.9

Three types of dredges, trailing suction hopper dredge, clamshell dredge and hydraulic cutterhead dredge, in various sizes were evaluated. The operations of the dredges are listed in Table 16.

Two equipment estimates were made to show sensitivity of equipment to the program. The production rates were modified for each site based on the characteristics shown in Table 15.

Transportation modes considered were the hopper dredge haul, combination of tug and scow and temporary or fixed pipelines. The transport by hopper dredge is the same cost shown in Table 16. Tugs and scows considered are listed in Table 17.

TABLE 16

HOURLY COSTS AND DAILY PRODUCTION
RATES FOR DREDGING EQUIPMENT

(1973 Price Level)

DREDGE TYPE	ESTIMATE 1 * PRODUCTION	HOURLY COST	ESTIMATE 2** PRODUCTION	HOURLY COST
	1000 cubic meters/day	dollars	1000 cubic meters/day	dollars
Hopper dredge				
Bottom dump	24.0	402	20.9	506
Direct pump	28.3	439	24.7	532
Clamshell				
Average plant				
9 cy	5.0	170	6.0	149
13 cy	7.2	195	8.6	165
18 cy	9.9	221	11.9	182
Special plant				
9 cy	6.0	179	-	-
13 cy	8.6	207	-	-
18 cy	11.9	237	-	
Hydraulic				
Average plant				
16 inch	7.6	157	9.6	146
24 inch	15.3	276	21.5	252
30 inch	22.9	351	33.6	317
36 inch	30.6	384	48.3	346
Special plant				
16 inch	9.6	163	-	-
24 inch	19.1	289	-	-
30 inch	28.3	370	-	-
36 inch	38.2	405	-	-

* ALL EQUIP: Annual Use 5000 hrs
HOPPER (EXISTING) Book Value $2 mil ; Remaining Life 13 yrs, Bulking Factor 12%
CLAMSHELL: Book Values $2.1, 2.9, 3.8, 2.5, 3.5, and 4.5 mil ; Life 20 yrs
HYDRAULIC: Book Values $1.1, 3.0, 4.4, 4.9, 1.3, 3.6, 5.3 & 5.9 mil ; Life 20 yrs

**ALL EQUIP: Annual Use 6500 hrs
HOPPER (NEW): Book Value $24 mil ; Life 50 yrs, Bulking Factor 25%
CLAMSHELL: Book Values $2.5, 3.5 & 4.5 mil ; Life 50 yrs
HYDRAULIC: Book Values $1.3, 3.6, 5.3 & 5.9 mil ; Life 50 yrs

TABLE 17

HOURLY COSTS FOR TUGS AND SCOWS
(1973 Price Level)

EQUIPMENT	HOURLY COSTS (DOLLARS)
1000 hp Tug	85.17
2000	99.92
3000	117.77
4000	155.76
5000	191.35
1000 c.y. Scow (bottom dump)	29.35
2000	35.90
3000	42.26
4000	45.80
5000	53.32
6000	58.26
1000 c.y. Scow (not bottom dump)	8.51
2000	12.50
3000	16.52
4000	18.74
5000	23.50
6000	26.60

* Based on 5500 hours per year.

Routes for fixed pipelines were located for each of two land disposal sites (Petaluma and Sherman Island) and to the 100-fathom ocean disposal site. Routes for temporary pipelines were established leading to the two land disposal sites and to a water terminus of a fixed pipeline system. Temporary lines leading from hydraulic dredges were limited to three miles. Table 18 gives cost estimates for pipeline and installation per linear foot.

TABLE 18

COST OF PIPELINES
(1973 Price Level)

Size	16-in	22-in	27-in	28-in	30-in	36-in
Pipe Cost	$22.15	$26.43	$30.00	$31.60	$35.00	$62.40
Installation	3.51	4.82	5.90	6.12	6.51	7.81
Total	$25.66	$31.25	$35.90	$37.72	$41.5	$70.21

For temporary pipelines removal costs were assumed to be one half of the installation costs.

Transfer equipment is needed whenever a change in transport mode is required. Costs were estimated for ten mobile (possible barge mounted) transfer stations. The capacity of the mobile stations ranges from 15,300 to 28,100 cubic meters per day (24 hour day). Per hour costs for these stations range from $47.34 to $131.40. Permanent transfer facilities near the center of gravity of dredging and at each of the two alternative land disposal sites were also considered.

The estimates of dredging equipment costs and productivity are necessarily subjective in nature because of the number of variables present in conceiving a systems approach. The costs were developed in 1973 and do not include overhead, profit, or supervision. Capital investment features were calculated with 6-7/8% interest. Operation of the system was based on a 20-year program. Table 19 summarizes the relative costs of dredging five projects with respect to alternative disposal sites using the various types of dredges. The least cost for each project is designated as 1.0. The systems used to develop the summary were those available with current technology. The model indicates that several theoretical disposal systems might minimize unit costs if present methods of disposal are considered unacceptable. These theoretical systems include the concept of a fixed pipeline to the 100-fathom disposal site. Many of the disposal methods which require high initial investment for pipelines, transfer facilities, land acquisition, etc. become economically practical when used to handle the average annual maintenance load of more than 7 million cubic meters from the San Francisco Bay system. Using these or other facilities in common for all dredging projects permits the full usage of engineering "economies of scale." This would require regional scheduling of operations. Conflicts which could develop with dredging needs would result in increasing the dredging quantities.

With the alternatives of fastlands or wetlands development, added costs are incurred for site preparation and operation. Table 20 presents estimated costs for the Petaluma and Sherman Island sites. Table 21 lists the costs associated with the Alameda Creek Marsh Development. The marsh site adjacent to the flood channel was an evaporation pond for salt production until 1965. About 535,000 cubic meters were placed in about 45 hectares.

As indicated by the Alameda Creek example, marsh development may be economically practical when used upon a case by case basis. The alternative is particularly attractive for small dredging projects which are located near suitable diked lowlands. The site, however, has a one time only use for disposal. Several reports have been published under the Dredged Material Research Program which provide information in addition to the supporting appendices. They are references 30 through 39 in the Bibliography.

TABLE 19

RELATIVE COST COMPARISON OF DREDGING
WITH ALTERNATIVE DISPOSAL SITES
(Idealized, systems dredging)

	HOPPER	HOPPER W/ PUMPOUT	HYDRAULIC CUTTERHEAD	CLAMSHELL
MARE ISLAND				
Carquinez	1.2-1.6	N/A	1.0-1.4	2.3-2.9
Alcatraz	4.8-6.2	N/A	N/A	2.7-3.0
100 Fathom	8.6-12.2	N/A	N/A	3.3-4.4
Land	N/A	2.6-2.8	3.3-3.9	3.9-4.7*
OAKLAND				
Alcatraz	1.1-1.5	N/A	1.3-1.7	1.0-1.3
100 Fathom	3.3-4.7	N/A	N/A	1.2-1.5
Land	N/A	1.3-1.5	2.8-3.2	1.7-2.1
REDWOOD CITY				
Land	N/A	1.2-1.5	1.0-1.4	1.5-1.7*
Alcatraz	2.9-4.2	N/A	N/A	1.6-2.1
100 Fathom	6.0-8.4	N/A	N/A	2.0-2.7
RICHMOND				
Alcatraz	1.1-1.6	N/A	1.8-2.3	1.0-1.3
100 Fathom	4.0-5.6	N/A	N/A	1.2-1.7
Land	N/A	1.5-1.6	2.8-3.2	1.8-2.2*
PINOLE SHOAL				
San Pablo	1.0-1.4	N/A	1.8-2.3	1.9-2.4
Alcatraz	3.0-4.2	N/A	N/A	2.2-2.5
Land	N/A	2.0-2.4	3.0-3.6	3.2-3.8*
100 Fathom	6.7-9.4	N/A	N/A	2.8-3.6

* Rehandle.

TABLE 20

SITE DEVELOPMENT COSTS FOR LAND DISPOSAL AREAS
(1973 Price Level Per Cubic Meter)

		Petaluma	Sherman Island
1.	Unprocessed Material* Unit Site development cost (Includes capital costs of acquisitions and development and O&M costs)	$0.25	$0.22
2.	Processed Material** Unit site development cost (Includes costs of (1) plus site preparation and processing costs)	$0.77	$0.86

* Material placed hydraulically in disposal ponds with no further treatment than decantation of water.

**Material which has, in addition the above, been improved by mechanical working.

TABLE 21

CONSTRUCTION AND PLANTING COSTS FOR ALAMEDA CREEK MARSH DEVELOPMENT
(September 1975 Price Level)

OPERATION	COSTS PER CUBIC METER	COST PER HECTARE
Site Acquisition	$0.20	$ 2,250
Site Preparation	0.15 1/	1,750
Dredging and Material Transport	1.60 1/	19,000
Planting	0.25	3,000
Total Costs	$2.20	$26,000

1/ Contract costs only, not including costs for engineering and design, and supervision and administration.

CONCLUSIONS

Based on the results of the various investigations conducted during the Dredge Disposal Study (reported in Appendices A through M) the following conclusions have been formulated regarding San Francisco Bay maintenance dredging and disposal activities:

- Higher concentrations of contaminants in dredged channels can be attributed to the finer grain size associated with maintenance dredging. Since dredged channels are out of equilibrium, forming a lower energy regime, finer sediments will tend to shoal. High contaminant levels in San Francisco Bay are normally associated with the finer sediments.

- The type of sediment and the degree to which it is disturbed determine the amount of sediment resuspension during dredging and the immediate release pattern during disposal at open water sites. The disturbance, including the adding and mixing with water, depends on the type and size of dredge, the efficiency of operation and the configuration of the shoal.

- The disturbance during sediment disposal is limited to the bottom two meters of the water column regardless of whether the sediment mounds or disperses. With hopper dredge operations, the sediments leave the disposal site typically within fifteen minutes of release and are quickly assimilated into the Bay sediment regime.

- The sediment regime of the Bay is a very dynamic system. Tests in the Bay show that within a month, dredged sediments are well distributed both horizontally (over 260 square kilometer study area) and vertically (in excess of 23 centimeters). About ten percent of the dredged sediment returns to the Mare Island Strait channel with disposal in Carquinez Strait. The majority of samples in the study area had less than four percent dredged sediment. Sediments entering San Pablo Bay for the most part are not carried directly to the ocean. Sediments are deposited, resuspended, recirculated and redeposited elsewhere with a net effect of sediment transport toward the ocean.

- Dredging and disposal in the Bay were not observed to cause changes in conductivity/salinity, temperature or pH. Temporary but marked water quality changes which were observed included reduction of dissolved oxygen, increases in suspended solids, and releases of trace elements, chlorinated hydrocarbon and nitrogen (nitrate and ammonia).

- Although large changes in water quality were demonstrated, no analogous changes in organisms were observed. Thus biological impact was not found to be synonymous with measurable water quality impact.

- Significant demonstrated biological effects resulting from in Bay dredging and disposal activities are limited to the reduction of the number and kinds of benthic organisms immediately following an operation and the net reduction of the p, p'-DDE desorption rate during disposal.

- The potential for adverse biological stresses from reduced dissolved oxygen and increased suspended solids concentrations is less during winter periods when water temperatures are lowest and dissolved oxygen levels highest. Furthermore, during this period eggs, larvae and juvenile organisms are at their lowest numbers in the water column.

- Release of toxicants during dredging and disposal operations seems to be at such low levels and to last for such short durations that their availability for uptake and accumulation is extremely limited.

- Salinity increases significantly intensify the potential for release of certain trace elements from resuspended sediments. Organisms, however, have been observed to have greater uptake rates during periods of decreased salinity and to have greater depuration rates in high salinity water. These two opposing conditions suggest that there is potentially a natural defense mechanism operating in organisms to safeguard them from excessive trace element accumulation.

- Increasing the efficiency of dredging operations in terms of minimizing energy losses in disturbing sediments and maximizing the collection of sediments whether by hydraulic cutterhead, clamshell or hopper dredge, will decrease the potential for adverse impacts.

- Increasing the dispersion of sediments dredged by hopper dredge in the Bay could have several positive effects. First, the potential of concentrated high suspended solids loading would be reduced. Second, both the intensity and duration of dissolved oxygen depressions would be reduced. Since these two conditions work synergistically, adverse biological effects would decrease. Third, since both toxicant release and uptake are concentration dependent, greater dispersion, although increasing the contact area of sediments for contaminant releases, should reduce the potential maximum release (concentration) at any one location and thus the potential organism uptake and accumulation. And finally, any nutrient or ammonia release would be quickly assimilated into the system, reducing potential localized biostimulation or toxicity. Changes in operational policies would have to be accomplished without significantly increasing the time frame of impact. Otherwise, possible mitigative advantages might be offset by increasing the duration of impact.

● The potential for long-term accumulation of contaminants by organisms from sediments dredged in harbor areas and disposed in the open bay is and has been a significant biological concern because of historically high contaminant levels in these harbor areas. Other areas in the Bay also have equally high contaminant levels because of their predominantly fine grain composition and high transport rate of resuspended sediments. Fine grain sediments naturally scavenge contaminants and wherever they are concentrated, contaminant levels will typically be high. Source control is the only effective method for controlling contaminant levels in these sediments. However, channel sediment sampling during the last two years (1975-76) seems to indicate that the contaminant levels in dredged channels have decreased to levels congruent with open areas of the Bay. This is probably the result of the elimination or improvement in quality of industrial and municipal discharges as required by both State and Federal regulatory agencies. As Bay sediment contaminant levels decrease, so will the potential for long-term toxicant accumulation.

● Open water disposal is not considered a significant blockage of the channels for migration of fish, particularly through Carquinez Strait. The plume, as monitored in the field, is confined to the bottom two meters of the water column, and its cross-section constitutes less than one percent of the Carquinez Strait cross section. The plume occurs in the disposal site less than one-quarter of the time (ratio of disposal time to total time).

● The movement of dredged sediments into the nodal zone in Carquinez Strait should cause no more impact on striped bass fingerlings and neomysis than those sediments naturally occurring in this zone. Sediment loading in the nodal zone is dependent on tidal forces and freshwater inflow. Dredged sediments do replace other sediments in the zone; however, unless a contaminant source significantly raises the concentrations in the dredged sediment, the two sediments should be physically and chemically similar.

● The transport of highly contaminated sediments from the Bay to deep water ocean disposal sites has the potential for creating long-term biological impact. When these sediments are released, mounding will generally occur (typically these sediments are cohesive and dredged by clamshell operation). These mounds will remain intact for long periods because of the lack of high current velocities to erode and disperse them. Since these contaminated sediments typically contain concentrations of organic materials, as well as toxicants, several factors higher than ambient levels, animals may be attracted to them as a concentrated food source. While feeding, these organisms are susceptible to uptake and accumulation of associated toxicants. This could be a particularly significant problem in the Gulf of the Farallones, a known nursery area for many commercially important species.

- The evaluation of potential impacts with either dispersion or mounding must be made on a case-by-case basis, considering the release of contaminants, the type of sediment and the sensitivity of both the water and the sediment system at the disposal site.

- Extensive land disposal for maintenance dredging projects does not appear to be a viable alternative to aquatic disposal at this time because of costs, identified technical difficulties and adverse environmental effects which may be involved. Potential problems include crossing of wetlands, rupture of dikes with earthquakes, mudflows, saline water loading and loss of irretrievable potential wetlands.

- Marsh development using dredged sediments should be viable on a case-by-case basis, particularly for one time only, small dredging projects which are located near suitable diked low lands, because of the environmental benefits achieved. Marshes are important to the estuary for their ability to oxygenate Bay waters, produce nutrients which serve as a base for the food web, capture ions, dissipate energy and provide wildlife habitat.

- Contaminant levels in estuarine organisms appear to be controlled by a limited number of synergistic factors. Suggested factors are the long-term process of sediment resuspension-recirculation, seasonal fluctuations in salinity and sources of contaminants both anthropogenic and geologic. The biological impact may be dependent on the form of contaminant and whether or not the sediment system can assimilate the contaminant loading. With the observed sorption-desorption by organisms and the fluctuating conditions in the estuary, impacts such as high accumulations, mutations and toxicity would not be expected unless the contaminant loading is foreign, in the case of synthetic chemicals, or above the assimilation capability of the estuary with the associated sediment regime, in the case of a low energy regime in which the changes in ambient conditions are great.

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CONVERSION FACTORS

If conversion from the Metric to the English system is necessary, the following factors apply:

LENGTH

1 kilometer (km)=10^3 meters=0.621 statute miles=0.540 nautical miles
1 meter (m)=10^2 centimeters=39.4 inches=3.28 feet=1.09 yards=0.547 fathoms
1 centimeter (cm)=10 millimeters (mm)=0.394 inches=10^4 microns (μ)
1 micron (μ)=10^{-3} millimeters=0.000394 inches

AREA

1 square centimeter (cm^2)=0.155 square inches
1 square meter (m^2)=10.7 square feet
1 square kilometer (km^2)=0.386 square statute miles=0.292 square nautical miles
1 hectare = 10,000 square meters = 2.471 acres

VOLUME

1 cubic kilometer (km^3)=10^9 cubic meters=10^{15} cubic centimeters=0.24 cubic statute miles
1 cubic meter (m^3)=10^6 cubic centimeters=10^3 liters=35.3 cubic feet=264 U.S. gallons=1.308 cubic yards
1 liter=10^3 cubic centimeters=1.06 quarts=0.264 U.S. gallons
1 cubic centimeter (cm^3)=0.061 cubic inches

MASS

1 metric ton=10^6 grams=2,205 pounds
1 kilogram (kg)=10^3 grams=2.205 pounds
1 gr (g)=0.035 ounce

SPEED

1 knot (nautical mile per hour)=1.15 statute miles per hour=0.51 meter per second
1 meter per second (m/sec)=2.24 statute miles per hour=1.94 knots
1 centimeter per second (cm/sec)=1.97 feet per second

TEMPERATURE

Conversion Formulas $\quad °C = \dfrac{°F-32}{1.8} \qquad °F = 1.8(°C) + 32$